



PHD

Enhancing start performance in the sport of skeleton

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ENHANCING START PERFORMANCE IN THE SPORT OF SKELETON

STEFFI LOUISE COLYER

A thesis submitted for the degree of Doctor of Philosophy

University of Bath
Department for Health
April 2015

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S. L. Colyer

ABSTRACT

Enhancing Start Performance in the Sport of Skeleton

Steffi L. Colyer, University of Bath, 2015

A fast start is considered to be crucial in skeleton with marginal gains in start performance perceived to make meaningful improvements to overall chances of success. Currently, knowledge surrounding the underlying determinants of start performance is sparse and training practices are based on limited scientific evidence. A series of investigations were conducted to advance this understanding.

Initial observations revealed similarities between dry-land push-starts and those on ice-tracks. However, the number of steps taken before loading was adjusted to seemingly accommodate unique track profiles and appeared to be influenced by physical capacity. Consequently, skeleton athletes completed multiple two-day testing sessions (four physical tests and biochemical analyses) across two seasons, alongside dry-land push-track tests. Additionally, body composition was assessed either side of selected training and competition blocks. Three independent physical factors (countermovement jump, sprint and force-power characteristics) were identified as fundamental to a fast push-start and a regression equation comprising these variables provided an accurate prediction of start ability ($R^2 = 0.86$). Testosterone appeared to influence push-track performance and lean mass accrual, however, retrospective biochemical analyses were deemed to have limited utility in applied practice. Conversely, the importance of monitoring body composition, particularly across competition seasons, was apparent and dual-energy X-ray absorptiometry is an appropriate tool to detect meaningful changes. A continuous sled velocity measure confirmed the contribution of physical capabilities to both the distance and velocity attained before loading. Importantly, loading phase success appeared independent of physical ability, perhaps warranting specific loading technique training. Finally, a trade-off between pre-load velocity and load effectiveness was evident, and experimentally modifying loading distance provided a promising approach to improve performance in developing athletes.

This thesis has informed skeleton training by identifying factors which contribute to performance, alongside approaches to thoroughly evaluate athlete progression and has introduced processes through which start performance can be enhanced.

PUBLICATIONS

Colyer, S.L., Stokes, K.A., Bilzon, J.L.J. and Salo, A.I.T. (2015). Improving skeleton athlete monitoring and talent identification processes using a series of multivariate analyses. *BASES Student Conference 2015*, Liverpool John Moores University, UK.

Colyer, S.L., Roberts, S.P., Robinson, J.B., Thompson, D., Stokes, K., Bilzon, J.L.J. and Salo, A.I.T. (2014). Use of dual-energy X-ray absorptiometry (DXA) to evaluate changes in body composition and the association with performance changes in skeleton athletes. *19th European College of Sport Science Congress*, Amsterdam, Netherlands.

Colyer, S.L., Salo, A.I.T., Bilzon, J.L.J. and Stokes, K.A. (2012). Consecutive days of push start testing may mask the effect of starting style in skeleton – A pilot study. *27th Meeting of the BASES Biomechanics Interest Group*, University of Ulster, UK.

DECLARATION OF WORK CONDUCTED

All of the data presented in this thesis were collected as part of this project except for the dual-energy X-ray absorptiometry scans for the rugby players, swimmers and athletics men and women in Chapter 6. These scans were carried out and analysed by a trained technician prior to the commencement of this project (between 2008 and 2011).

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NOMENCLATURE AND DEFINITIONS

Abbreviations used for terminology throughout the thesis

1RM	One-repetition maximum
ARFD	Average rate of force development
ARMSS	Applied research model for the sport sciences (Bishop, 2008)
BW	Body weight
CI	Confidence interval
CK	Creatine kinase
CM _{disp}	Centre of mass displacement
CMJ	Countermovement jump
CV	Coefficient of variation
DHT	Dihydrotestosterone
DXA	Dual-energy X-ray absorptiometry
FM	Fat mass
F _{max}	Theoretical maximum force
FP _{max}	Force produced at maximum power
FV _{grad}	Gradient of the force-velocity trendline
ICC	Intraclass correlation coefficient
KEA	Knee extension assessment
LM	Lean mass
LLM	Leg lean mass
MPP	Mean positive power
MVC	Maximum voluntary contraction
PB	Personal best
PCA	Principal component analysis
P _{max}	Maximum power
SEE	Standard error of the estimate
SF	Step frequency
TBM	Total body mass
TEM	Typical error of the measurement
V ₁₅	Sled velocity at 15 m mark
V ₃₈₋₄₅	Sled velocity between 38 and 45 m marks
V _{max}	Theoretical maximum velocity

Definitions of key terms used throughout the thesis

<i>Start time</i>	Time taken to cover the start phase (15-65 m on ice-tracks, 15-55 m on the Bath dry-land push-track)
<i>Loading phase</i>	The transition between bent-over running (and pushing the sled) to the prone driving position
<i>Physical characteristics</i>	The attributes of athletes which are quantified through physical testing
<i>Performance</i>	The success with which a task is completed
<i>Push performance</i>	The success with which the start phase is completed

CHAPTER 1: INTRODUCTION

1.1. Research overview

Skeleton was introduced as a permanent feature of the Winter Olympic programme for the 2002 Games in Salt Lake City and rapidly became known as one of the fastest winter sports. Skeleton competitions are currently limited to only 14 ice-tracks worldwide which range from 1200-1800 m in length and vary considerably in profile (FIBT, 2015b). An explosive push phase initiates each skeleton run, in which athletes sprint and push the sled in a bent-over position for around 3.5-4.5 seconds before launching themselves forwards to 'load' the sled, typically 20-30 m from the starting block (a wooden beam embedded in the ice across the track). In the driving phase which follows, athletes adopt a prone position and negotiate a series of corners to reach speeds in excess of $145 \text{ km}\cdot\text{h}^{-1}$ and experience forces of up to 5g.

The nature of the race timing in skeleton is unconventional (in comparison with many other sports), as the interruption of a photocell located 15 m from the starting block initiates the clock. When a skeleton athlete passes the 65 m photocell, the start phase is complete and the 15-65 m 'start time' is often used to gauge the success of the push. Overall race outcome is then determined by the cumulative final descent times across two or four heats, depending on the competition. Considering the length of the track and the many opportunities to make costly driving errors, skeleton races can be decided by remarkably small margins. For example, at the 2010 Winter Olympics in Vancouver, the gold medal in the men's competition was decided by only 0.07 s (after four runs, cumulative time ~ 3.5 mins; FIBT, 2015a). At the most recent Olympics in Sochi, the winning margins were much larger than this (0.81 and 0.97 s in the male and female skeleton events, respectively). However, the difference between winning the bronze medal and finishing in fifth place was comparably small (only 0.10 s in the women's competition).

The start phase is considered to be a crucial component of performance in all sliding sports (Brüggemann et al., 1997; Zanoletti et al., 2006) and it is generally believed that marginal gains in the start phase can make meaningful differences to overall chances of success. In fact, at the most recent Winter Olympics in Sochi, the gold medallists accumulated start time gains of 0.43 and 0.83 s over the silver medallists in the male

and female skeleton events, respectively (FIBT, 2015a). Moreover, the advancements in the understanding of sled mechanics during steering (Sawade et al., 2014), which have accompanied the maturation of skeleton, may ultimately narrow the variation in driving phase performance. Thus, a fast start phase is expected to become progressively more important over time (Bullock et al., 2008). Considering the emphasis placed on a fast start time, it is surprising how few research studies have been conducted to investigate which components contribute to a successful push-start. As such, training prescription and coaching methods are currently based on limited scientific evidence. Thus, much scope exists for research findings to improve training practices which could lead to enhancements in start performance and overall chances of success in international skeleton competitions.

Ice-tracks are closed during the summer months and thus, skeleton athletes typically undergo an intensive period of dry-land training. Across this season, athletes endeavour to develop their physical abilities through resistance training and refine their push-start skills on dry-land push-tracks. This is under the premise that any observed improvements will translate to ice-track start performances. To the author's knowledge, however, the presumed association between ice-track and dry-land starts has not been studied to date.

Anthropometric and physical characteristics have previously been described for a group of elite US skeleton athletes, and associations between dry-land push-track performance and measures of lower limb power were identified (Sands et al., 2005). This may have somewhat contributed to the emphasis now placed upon vertical jump and sprint measures when screening potential skeleton athletes (Bullock et al., 2009a). Yet, no attempt has been made to ascertain the relative influences of different physical factors on start performance. Current skeleton athlete monitoring processes could therefore likely be improved by the evaluation of the independent contributions of physical test scores to the prediction of push performance. Such information could allow more accurate and efficient evaluation of an athlete's progress and the success of prescribed training.

In recent times, advancements in sports science have introduced a plethora of sophisticated equipment and measurement techniques in which to supplement the more

conventional physical testing batteries. For example, the composition of individual body segments can be quantified using increasingly more accessible technologies such as dual-energy X-ray absorptiometry (DXA) scans (Stewart and Hannan, 2000a). Additionally, the development of biochemical assays has introduced further tools which may provide additional insights into the physiological status of an athlete. For example, circulating hormones appear to have a potentially important influencing role on the neuromuscular system and the expression of athletic performance (Crewther et al., 2011). However, fundamental (and sometimes overlooked) considerations when using any diagnostic marker or monitoring apparatus relate to the validity and reliability of the measurement. As these techniques are typically expensive, sometimes invasive and can be time-consuming, their utility to inform applied practice must be scrutinised before they are routinely used to monitor athletes.

Previously, broad characterisation of the start phase in skeleton has associated start time with certain discrete velocity measures (15 and 45 m sled velocity) on three ice-tracks (Bullock et al., 2008) and split times on a dry-land push-track (Sands et al., 2005). However, a major limitation of these discrete variables is the inability to detect short-lived, but potentially important, changes in velocity. Thus, a continuous measure is required to fully characterise the sled velocity changes typically exhibited across the start phase and determine which aspects of this profile are associated with superior performance. Such novel information could provide interesting insight, through which potential start performance enhancing interventions may emerge.

1.2. Statement of purpose

The aim of this thesis was to increase the understanding of the underlying determinants of skeleton start performance in order to inform and enhance training practices.

1.3. Research questions

To achieve the stated aim, a series of research questions were developed. A paucity of research exists surrounding the skeleton start and thus, initial investigations should take the form of observational analyses to provide an account of how the start is typically performed (Yeadon and Challis, 1994). It is generally believed that push-starts performed on a dry-land push-track simulate those on ice-tracks. Indeed, previous

studies have used dry-land performances to differentiate current (Sands et al., 2005) and potential (Bullock et al., 2009a) skeleton athletes. However, to the author's knowledge, no studies have investigated this association and thus, the first research question was formulated:

i. How do skeleton athletes perform the start phase on different tracks and are dry-land push-starts comparable with those on ice-tracks?

Having characterised some of the differences in the way individual skeleton athletes perform the skeleton start, an investigation into the physical variables which are likely to contribute to this variation, and subsequently determine start performance level, is warranted. A programme of ongoing physical monitoring is typically adopted to allow the evaluation of athlete development and the success of the prescribed training. However, to ensure this process is as efficacious as possible, physical test batteries should ideally focus on independent performance determining constructs (Newton et al., 2011). With this in mind, the second research question was developed:

ii. What are the key physical characteristics underlying skeleton start performance?

Acute biochemical responses to an exercise bout are considered to be necessary stimuli to elicit adaptive training outcomes (Crewther et al., 2006). In particular, testosterone purportedly plays a role in the training process by regulating hypertrophy (Bhasin et al., 2001b). However, this association has come under scrutiny recently (West and Phillips, 2012) and alternative short-term actions of testosterone have been proposed (Crewther et al., 2011), which appear to influence training performance (Cook and Beaven, 2013). Further work is needed to elucidate the significance of these biochemical markers in well-trained athletes. Consequently, the third research question was posed:

iii. What are the biochemical responses to physical exercises and does testosterone influence performance and lean mass accrual?

Sophisticated imaging technologies (such as DXA scanning) have become progressively more accessible to sports scientists in recent times, enabling more precise and detailed estimation of athletes' body composition (Stewart and Hannan, 2000a). However,

factors which are known to influence the estimation accuracy of DXA scans (e.g. fluid intake; Nana et al., 2012) are difficult to restrict during training seasons and the resultant influence on measurement accuracy is seldom considered. Thus, the ability of DXA to detect small, but worthwhile, body composition changes is yet to be determined in this context. This resulted in the formation of the fourth research question:

iv. Can dual-energy X-ray absorptiometry detect true body composition changes in trained athletes and what are the performance implications of these changes?

Discrete temporal and velocity measures (e.g. 15 m time, and 15 and 45 m velocity) have revealed differences in the sled acceleration profile amongst skeleton athletes, with loading phase success implicated as a possible source of this variation (Bullock et al., 2008). A continuous measurement of sled velocity is required to better understand these sources of variation in the acceleration profile. Such novel analysis could provide important insight into the performance determining features of the sled velocity profile. This formed the basis for the fifth research question:

v. Which aspects of the sled velocity profile are associated with superior skeleton start performance?

Skeleton athletes are known to adopt individual starting strategies (for example, number of steps and time taken before loading) in elite skeleton races, which seem to be adjusted to accommodate the unique profile of tracks (Bullock et al., 2008). However, the influence of these alterations on the sled velocity profile has not been investigated and it is currently unknown whether changes to loading distance can result in an overall faster start phase. Consequently, the final research question was developed:

vi. How do alterations to loading distance and track profile influence sled velocity and can modifications to loading distance enhance performance?

These six research questions provided direction to this programme of work. Specific investigations were designed to address each of these questions and achieve the aim of this thesis.

1.4. Organisation of chapters

1.4.1. Chapter 2 – Literature review

A review of the literature which is pertinent to this thesis is provided in Chapter 2. A discussion of the current research within the skeleton start is provided, including the importance of this phase to overall performance, alongside the extent to which the start phase and physical abilities of skeleton athletes have previously been characterised. As research within skeleton is relatively scarce, literature concerning similar movements is then considered, with the relevance to skeleton start performance discussed where appropriate. This includes a review of the current knowledge surrounding both the physical and biomechanical determinants of sprint starts, as well as sprint start training methods and the associated musculoskeletal adaptation. Alongside the identification of sprint start performance determinants, several physical tests and physiological markers are outlined which may provide additional insight when monitoring athletes.

1.4.2. Chapter 3 – Descriptive analysis of skeleton start performance: A comparison between dry-land and ice tracks

This chapter characterises push-start performance on a dry-land push-track and two ice-tracks using selected start technique descriptors. An examination of the variation in these descriptors both between athletes and across tracks is then provided. Group-based analyses of average step frequency and number of steps is also conducted to better understand how these variables differ across tracks and how they relate to start performance. Finally, correlational analyses and performance-based rankings are used to evaluate whether the dry-land push-starts are comparable with those on two different ice-tracks.

1.4.3. Chapter 4 – Developing an understanding of the key physical characteristics underlying skeleton start performance

An investigation into the physical determinants of skeleton start performance is presented in Chapter 4. Two-day physical testing sessions were performed at a series of time points across two seasons. Correlational analyses are used to assess the association between selected physical test scores and push performance. A series of multivariate analyses are then conducted (consisting of principal component analysis, multiple regression and *K*-fold cross-validation). These analyses firstly reduce the large number

of output measures to a small set of independent variables, before their ability to accurately predict push performance is evaluated.

1.4.4. Chapter 5 – Biochemical responses and the influence of testosterone on start performance and lean mass change in skeleton athletes

This chapter firstly describes the responses of selected serum-bound biomarkers (testosterone, cortisol, dihydrotestosterone and creatine kinase) to physical exercises in skeleton athletes. Within-athlete correlations are used to evaluate the associations between circulating testosterone and physical performance. The controversial role of testosterone in hypertrophy is then explored by assessing the correlations between circulating testosterone and lean mass accrual across a training season. Finally, the relationship between creatine kinase and muscle soreness is assessed using within-athlete correlational analysis.

1.4.5. Chapter 6 – Evaluating longitudinal changes in body composition and the influence of these changes on physical performance

The reliability of DXA to detect meaningful body composition changes in the applied athletic setting is investigated in Chapter 6. Firstly, typical errors involved in DXA measurements are quantified in a large cohort of athletes from diverse sports. These errors are subsequently used to assess whether the longitudinal body composition changes exhibited by skeleton athletes across specific training and competition blocks are indeed ‘true’ changes. The influence of these changes on physical performance is then assessed using correlational analyses.

1.4.6. Chapter 7 – Investigating changes in sled velocity across the start phase

This chapter consists of two parts: part I initially examines the velocity profile of the sled during the start phase and introduces several novel start performance descriptors and a unique sled acceleration index. Multiple regression analysis is then used to identify which aspects are important to overall start performance. Part II of this chapter assesses the separate effects of altering track profile and loading distance on the sled velocity profile and the previously identified (part I) performance determining descriptors. In the final part of this chapter, the potential to enhance start performance through altering loading distance is evaluated on an individual athlete basis.

1.4.7. Chapter 8 – General discussion

In Chapter 8, the primary findings of this research are discussed and the research questions introduced in section 1.3 are addressed. An overall discussion of the advancement in knowledge is then provided alongside the practical implications that have emerged from this work. Following this, the impact of this research on ice-track start performance is evaluated and the methodological principles adopted throughout this thesis are discussed. Finally, the potential directions for future research are proposed.

CHAPTER 2: LITERATURE REVIEW

2.1. Introduction

A skeleton run consists of two distinct phases: the start phase (where athletes sprint and push the sled in a bent-over position) and a driving phase (where athletes adopt a prone position and negotiate a series of corners). Although a powerful start is widely accepted to be a crucial component for success in skeleton, the underlying determinants are relatively unexplored. As a result of this lack of knowledge, coaches must currently base their training methods and coaching techniques on primarily anecdotal evidence. This chapter firstly outlines the previous research conducted within skeleton start performance, before discussing a potential research pathway through which sport science can enhance performance. The sections which follow will evaluate the relevant literature surrounding the physical and biomechanical determinants of sprint start performances which can, in part, be translated to the skeleton start. Additionally, the current knowledge surrounding neuromuscular adaptation to resistance exercise, the transfer of these adaptive responses to sprint start performance, and considerations surrounding monitoring protocols will be reviewed.

2.2. Skeleton start performance

2.2.1. Importance of the start phase to overall performance in skeleton

It is commonly believed amongst coaches and athletes that a 0.1-second start time gain translates into a 0.3-second lead by the finish line (anecdotal evidence). Correlational analyses (Zanoletti et al., 2006) have revealed moderate relationships (combined $r = 0.48$ and 0.63 for male and female competitions, respectively) between start time and final descent time across 24 competitions during the two seasons which followed skeleton's permanent introduction into the Winter Olympic programme (2002-2004). Thus, start time was found to explain 23 and 40% of the variance in overall performance across these races for male and female skeleton athletes, respectively. Prior to this, stronger relationships ($r = 0.88$ and 0.74) between start time and final descent time had been reported in bobsleigh and luge, respectively (Brüggemann et al., 1997). Analyses utilising a median split across final descent times revealed that skeleton athletes with superior overall race performance had significantly ($p < 0.05$) faster push times than their weaker counterparts across the first heats of the races (Zanoletti et al., 2006). This effect was not observed in the second heat, which may be a result of increased

homogeneity of the group because only the top 20 competitors are permitted a second run in World Cup races. However, in the same study, changes in start time between heats did not reflect changes in final race time. Thus, although a fast start may be a prerequisite for success in skeleton, start performance enhancement does not guarantee an improvement in overall descent times and a multitude of other factors (most notably driving ability) contribute to race outcome. However, it seems unlikely that achieving a faster push time could somehow be harmful to overall performance and thus, a specific aim must be to enhance the start phase.

In order to investigate the relationship between start performance and final descent time further, eleven World Cup tracks (out of a total 14 tracks worldwide) were classified by experts (two skeleton coaches and an Olympic medallist) into four categories. These groupings relate to the unique characteristics of each start track (such as the gradient and proximity of first corner) as well as the technical difficulty of the driving phase (Bullock et al., 2009b; Table 2.1).

Table 2.1. Classification of World Cup ice-tracks (Bullock et al., 2009b).

Pure push tracks	Tracks with a large push component	Tracks with a large driving component	Pure driving tracks
Igls, Austria	Königssee, Germany	St. Moritz, Switzerland	Sigulda, Latvia
Winterberg, Germany	Calgary, Canada	Lillehammer, Norway	Altenberg, Germany
	Lake Placid, USA		Torino, Italy
	Park City, USA		

When these individual races are considered in isolation, the relationships between start time and final descent time have been shown to vary (Bullock et al., 2008; Bullock et al., 2009b), with stronger correlations reported on tracks which are considered to have larger push components. For example, at Lake Placid (classified as having a large push component) a large correlation ($r = 0.51 \pm 0.29$) between push time and finish time was reported. Conversely, weak associations between start time and final descent time at St. Moritz ($r \pm 90\% \text{ CI} = 0.14 \pm 0.37$; large driving component) and Sigulda (pure driving track; $r = 0.03 \pm 0.38$) were reported. Additionally, Bullock et al. (2009b) found run-to-run variability (within-athlete) to increase with technical difficulty, perhaps indicating that athletes were more likely to make errors on tracks with larger driving

components. When considered collectively, driving mistakes seem to be more common and determine success to a greater extent on tracks with greater technical difficulty than on tracks with larger push components (where a fast start time appears to have a greater influence on race outcome).

2.2.2. Performance characteristics of the skeleton start

Only one study has attempted to characterise skeleton start performance, in which 15 and 45 m sled velocities were quantified on three ice-tracks (Lake Placid, Sigulda and St. Moritz) along with the number of steps and time taken to load the sled (Bullock et al., 2008). A significantly greater number of steps (18 ± 1 and 17 ± 2 vs. 14 ± 1), increased time to load (4.38 ± 0.24 and 4.27 ± 0.20 vs. 3.60 ± 0.15 s), and higher 45 m sled velocity (11.44 ± 0.21 and 11.27 ± 0.18 vs. 10.97 ± 0.43 m·s⁻¹) was recorded at Lake Placid and Sigulda compared with St. Moritz, respectively. Thus, certain tracks appear to allow athletes to take a greater number of steps, take more time to load and attain higher velocities, presumably reflecting the unique characteristics of each track. For example, the start phase at Lake Placid is a longer and flatter profile compared with at St. Moritz, which seemingly allows athletes to take a greater number of steps before loading the sled, accelerate the sled further and attain faster 45 m velocities. This may provide faster starters (those with superior physical capacity) with a greater opportunity to achieve higher velocities and accumulate large start time gains over their slower counterparts. It may be that these margins are then difficult to recover in the driving phase, as less run-to-run variability is observed (Bullock et al., 2009b), perhaps reflecting less opportunities to make errors. This could explain why Lake Placid is considered to have a larger push component (Bullock et al., 2009b; Table 2.1) and why the start phase determines overall performance to a greater extent than at St. Moritz (Bullock et al., 2008). However, previous investigations have not assessed whether these (and other) start performance characteristics are related to the physical capacity of the athletes.

A further noteworthy finding from the Bullock et al. (2008) study was an ‘imperfect’ relationship between 15 m velocity and time to 15 m ($r \pm 90\%$ CI = -0.71 ± 0.20 and -0.73 ± 0.19 for Sigulda and St. Moritz, respectively) suggesting between-athlete variation in the sled velocity profile across the initial 15 m section of the track. As competition timing is initiated by the triggering of the 15 m photocell, the time taken to

reach this position on the track should perhaps be considered an irrelevant start performance measure. This is because athletes could increase the time to the 15 m mark in an attempt to maximise 15 m velocity (for example, by taking longer ground contacts in an effort to increase horizontal net impulse), with no detrimental effects to the overall descent time (the determining factor of success). Similarly, between-athlete variation in the sled velocity profile between the 15 and 45 m marks has been illustrated by 'imperfect' relationships between 15 m sled velocity and 45 m sled velocity at Sigulda and St. Moritz ($r \pm 90\% \text{ CI} = 0.71 \pm 0.20$ and 0.67 ± 0.22 , respectively; data not available for Lake Placid). This is most likely attributable to differences in both downhill running ability and the velocity changes during the loading phase. A continuous velocity profile across the entire start phase is required to better understand the sources of this variation.

2.2.3. Physical characteristics of skeleton athletes

To the author's knowledge only one study has investigated the physical attributes of skeleton athletes, in which fourteen (7 male, 7 female) athletes from the US National Skeleton Team were characterised (Sands et al., 2005). Anthropometric testing revealed that male athletes in this group were predominantly mesomorphic in body stature, whereas female athletes exhibited a wider range of somatotypes. High lower limb power, as assessed through a series of vertical jumps under various loads, was found to strongly relate ($r \pm 90\% \text{ CI}$ ranged from -0.73 ± 0.24 to -0.92 ± 0.09) to faster dry-land push-track performance (10, 15, 20, 25, 30 m times). As previously discussed in section 2.2.2, it could be argued that the 10 and 15 m times are not appropriate performance measures because competition timing does not start until the 15 m mark (and therefore the variance in velocity-time profiles may invalidate these performance measures). Nonetheless, strong negative associations between vertical jump performance and 15-30 m push times were observed (r ranged from -0.89 to -0.97) and therefore lower limb power should be considered an important physical attribute for skeleton athletes to possess. Additionally, faster upright sprint times have also been shown to be very strongly related ($r \pm 90\% \text{ CI}$ ranged from 0.85 ± 0.15 to 0.98 ± 0.02) to push performance (Sands et al., 2005). Strength and power training, alongside high-velocity sprint-based exercises, have therefore been recommended (Sands et al., 2005) and are widely prescribed to skeleton athletes in an attempt to improve lower limb power and sprint ability and thus, potentially enhance skeleton start performance. Moreover,

measures of sprint ability and lower limb power have been used as criteria in talent identification programmes (Bullock et al., 2009a).

Sands et al. (2005) acknowledged that skeleton was a relatively young sport and therefore the physical requirements of the sport may change over time as the sport matures. In fact, some members of the US skeleton squad in the aforementioned study were not accustomed to resistance training and therefore these results may not be directly applicable to current skeleton athletes, who typically have an extensive training history. Additionally, many of the physical test scores which were found to relate to start performance measures are likely to covary, perhaps reducing the efficiency of the athlete monitoring process. Although a key set of independent physical characteristics have been identified in certain sports (e.g. in gymnastics; Douda et al., 2008), no attempt has been made to ascertain such aspects of physical performance which are important for skeleton athletes to possess.

2.3. Sport performance enhancing research

Research surrounding the factors which contribute to fast skeleton starts is clearly sparse and therefore, the superior training and coaching methods in which to enhance performance are yet to be scientifically determined. Bishop (2008) has previously proposed a framework which can be used to direct research with the ultimate aim to improve sport performance. The multi-stage Applied Research Model for the Sport Sciences (ARMSS) outlines a logical progression of research stages from the inception of a problem to the implementation of potential performance enhancing interventions (Figure 2.1). Although eight stages of the model exist, these can be simplified into three main phases: description, experimentation and implementation. Thus, the ARMSS pathway aims to firstly identify the key performance issues, before experimentally testing how modifiable they are and finally, the potential to influence real-world performance is assessed.

One of the first examples within sport and exercise science where this framework can be observed involves the role of anaerobic thresholds in endurance performance. Although this may not be directly applicable to the skeleton start, it provides a good example of how research can be progressed in line with the ARMSS model. Burke (1976) had

shown $\dot{V}O_2$ max to be a good predictor of distance running performance ($r \pm 90\% \text{ CI} = 0.90 \pm 0.05$) in a heterogeneous group, however, it was also recognised that athletes with similar race velocity could vary considerably in $\dot{V}O_2$ max (Costill, 1970). Therefore, a need to investigate alternative determinants of endurance performance was proposed (stage 1 of the ARMSS).

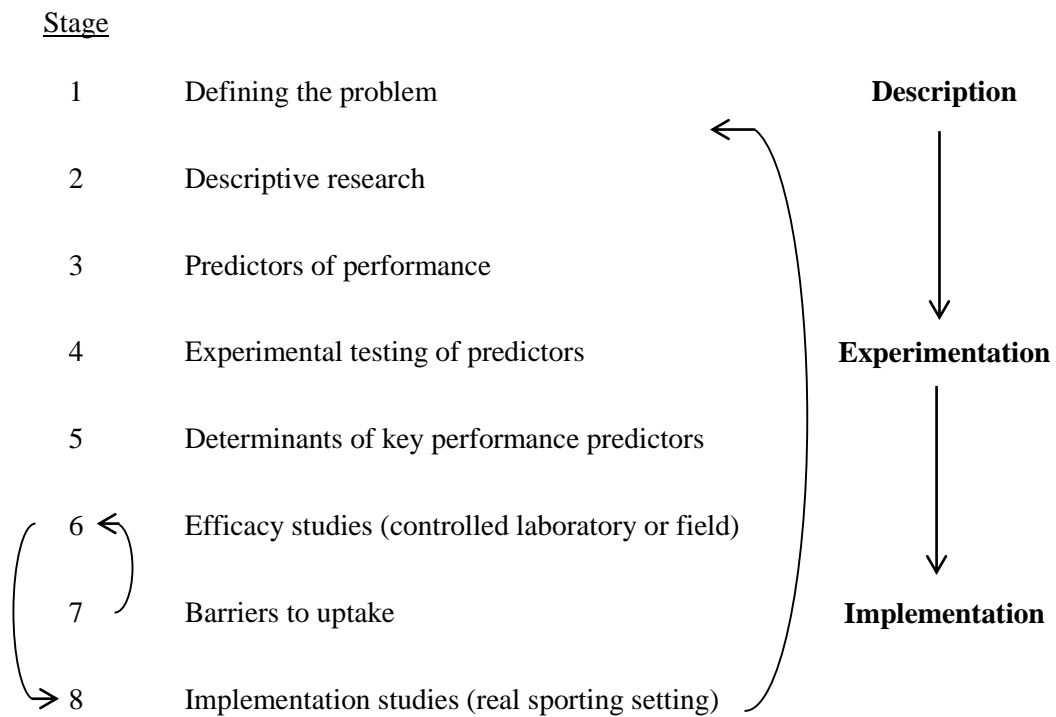


Figure 2.1. An applied research model for the sport sciences (from Bishop, 2008). Curved arrows represent the iterative nature of the model.

Descriptive analysis (ARMSS stage 2) documented increases in lactate production at higher exercise intensities (Bloom et al., 1976) and blood lactate accumulation was identified as a potentially important performance-limiting factor (Åstrand and Rodahl, 1977). Studies were then devised to investigate the relationship between the predictor variable (lactate threshold) and performance (distance running), which forms stage 3 of the ARMSS. For example, Sjödin and Jacobs (1981) revealed very strong relationships ($r \pm 90\% \text{ CI} = 0.96 \pm 0.04$) between lactate threshold and marathon running velocity. The identification of such strong predictors of performance is often considered to warrant the inclusion of the associated physical tests in longitudinal monitoring programmes which assess an athlete's progress and may also provide benchmarks for

talent identification initiatives. In fact, physiological monitoring of a female 3000 m Olympic runner across a five year period revealed lactate threshold as a more informative indicator of training progress than $\dot{V}O_2$ max (Jones, 1998). Additionally, the performance predictors which emerge can be used to guide training and coaching practices towards the key performance issues. However, as these relationships are not necessarily causal, stage 4 of the ARMSS involves the manipulation of one predictor variable (whilst controlling or matching other variables) and measuring the subsequent effect on performance. For example, Coyle et al. (1988) matched two groups of endurance cyclists based on $\dot{V}O_2$ max and found these groups to exhibit differing lactate thresholds. The fact that athletes with higher lactate thresholds exhibited superior endurance was considered to provide additional support for a causal effect of lactate threshold on performance.

Studies which fall in subsequent stages of the ARMSS (stages 5 to 8) seek to determine the most effective interventions (training, technique, nutrition etc.) to alter performance. In the elite sport setting, these studies are particularly difficult to implement, perhaps due in part to the apprehension of athletes and coaches to adhere to the level of control required in these experimental studies (Kearney, 1999). Additionally, it could be argued that assigning a control group alongside a potentially performance enhancing treatment group has ethical considerations (McNamee et al., 2007). Nonetheless, such studies are possible to conduct in some settings. For example, in the lactate threshold example, Evertsen et al. (2001) identified high-intensity interval training to increase the lactate threshold of cross-country skiers to a greater extent than moderate intensity continuous training (ARMSS stage 5). Moreover, it was shown that the training-induced increase in lactate threshold also resulted in improvements in 3000 m running time in the laboratory setting (Esfarjani and Laursen, 2007), a study which falls within stage 6 of the ARMSS. Although high-intensity training may be a common component of training programmes, no study has been published to show the efficacy of such an intervention to improve competition performance in elite endurance athletes (stages 7 and 8). In reality. Such studies are typically very difficult to conduct in this context. Nonetheless, the logical pathway outlined by Bishop's ARMSS model provides a solid framework upon which the progress of investigations within this thesis can be based.

In order to logically investigate a relatively unknown technique, such as the skeleton start, it is important to extract relevant information from previous research within similar athletic movements and attempt to translate this to the performance in question. In fact, Bishop (2008) emphasises the importance of having a thorough understanding of the relevant literature in stage 1 of the ARMSS prior to planning subsequent stages. This can guide the research design with sound scientific reasoning and provide rationale for the methods used. There are, for example, some clear similarities between the demands of skeleton start performance and those of athletic sprint starting (maximally accelerating a mass from a starting block). Consequently, previous research findings within this event can provide essential guidance to the initial stages of this thesis. Naturally, there are also important differences (an obvious example being running posture) and the application of the sprint start findings to skeleton must therefore be carefully deliberated. The following section will firstly outline the current knowledge surrounding the key physical abilities which relate to sprint start performance (across the acceleration phase, from the block to maximum velocity attainment). The methods used to monitor these parameters will also be described and evaluated.

2.4. Physical determinants of sprint start performance and the associated measurement techniques

2.4.1. Anthropometry

Limited information exists regarding the anthropometric characteristics underlying sprint start performance. In ten male competitive sprinters, Maulder et al. (2006) investigated the association between accelerative performance and various anthropometric variables (including tibia length, tibia to floor length, femur length, hip width and shoulder width). No statistically significant ($p > 0.05$) associations were reported between 10 m sprint performance and any of these anthropometric measures ($r = 0.50, 0.42, 0.40, 0.22$ and 0.18 , respectively). It therefore appears that other physiological or mechanical factors contribute more substantially to sprint start performance than body stature.

Many athletic performances, including sprinting, are largely determined by the power-to-body weight ratio (Cronin and Hansen, 2005). Theoretically, excess adipose tissue increases the passive mass (which is unable to produce force) and thus, the

muscular effort necessary to accelerate an athlete's centre of mass (CM). Athletes with greater muscle mass and less fat mass are, therefore, more likely to exhibit a higher power-to body mass ratio and therefore greater accelerative ability, than those with less muscle mass and/or greater fat mass. Indeed, higher skinfold thickness (sum of seven sites) was associated with slower 10 m ($r \pm 90\% \text{ CI} = 0.61 \pm 0.25$) and 30 m ($r = 0.53 \pm 0.28$) sprint times in a group of professional Australian Rules football players (Le Rossignol et al., 2014).

Additionally, Perez-Gomez et al. (2008) have found higher relative leg lean mass (percentage of total body mass), estimated by dual-energy X-ray absorptiometry (DXA), to be related to better 30 m sprint times ($r \pm 90\% \text{ CI} = -0.42 \pm 0.25$) in female physical education students. The authors also showed lower body fat percentage and increased total lean mass to significantly contribute to faster 30 m sprint times, along with higher peak power during vertical jumping. This finding suggests that, in conjunction with raw physical ability, body composition is also an important and independent contributing factor to 30 m sprint time. In contrast to this finding, Kukolj et al. (1999) found lean body mass and relative lean mass (as estimated using skinfold measurements and associated equations) to be unrelated to sprint performance during the initial acceleration phase (0.5-15 m time; $r \pm 90\% \text{ CI} = -0.09 \pm 0.34$ and 0.06 ± 0.34 , respectively) and the acceleration phase to maximum velocity (15-30 m; $r = -0.12 \pm 0.34$ and -0.03 ± 0.34 , respectively). This discrepancy is perhaps due to differences in measurement techniques between the studies, as the accuracy of regression equations to predict body composition from skinfold measurements is generally poor (Rodríguez et al., 2005). For this reason, it is important to consider the relative advantages and disadvantages of the various body composition assessment methods, as these vary greatly in terms of accuracy, as well as practicality and cost.

Skinfold thickness measurements are perhaps the most commonly used field based method for measuring body composition in athletic populations. Callipers are used to measure the thickness of a double layer of skin and the underlying subcutaneous adipose tissue at a series of four, seven or eight sites across the body. These measurements can be summed or entered into predictive equations (e.g. Jackson and Pollock, 1978) to estimate body fat percentage, fat mass and lean mass. A potential downfall of this method is the fact that visceral (intra-abdominal) fat is not included and

measurement errors are therefore inevitably introduced. Nonetheless, if taken by the same experienced or trained tester, a sum of skinfold measurements seems to provide a reliable, practical and quick method in which to evaluate body fat changes across a training season (Klipstein-Grobusch et al., 1997).

A number of laboratory-based methods also exist with the more expensive imaging techniques (such as dual-energy X-ray absorptiometry, DXA) regarded as the ‘gold standard’ methods. Originally used as a tool to measure bone density, DXA scans are now widely utilised to estimate body composition and (unlike other scanning techniques such as computer tomography) only introduce a minimal dose of radiation (Stewart and Ackland, 2011). The individual maintains a supine position on the scanner for typically 4-15 minutes whilst two X-ray waves of different energies are passed through the body. These waves are then attenuated according to the atomic weight of the molecules which obstruct their path (Pietrobelli et al., 1996). Thus, lipids, bone and fat-free mass attenuate the X-rays to varying degrees and the associated software is able to detect the composition of each pixel based on known tissue equivalents. DXA scans have been validated using phantom (Haarbo et al., 1991) and animal models (Brommage, 2003), as well as against computer tomography scan results (Salamone et al., 2000). Whole body and/or regional composition can be estimated with good precision, although regional estimation appears to be less precise (Fuller et al., 1992; Nana et al., 2012).

Previously, DXA has been described as a sensitive method in which to detect seasonal changes in athlete body composition as these changes appeared to reflect shifts in the emphasis of training (Egan et al., 2006; Harley et al., 2011). However, factors such as hydration status and glycogen content have been shown to influence DXA scan results (Horber et al., 1992; Pietrobelli et al., 1996). Thus, a meticulously controlled protocol has been recommended and shown to minimise the measurement errors (Nana et al., 2012, 2013). This procedure requires athletes to be fasted, rested and hydrated prior to the scans, which may not always be realistic in the applied setting. The impact of increased measurement errors on the ability to detect important body composition changes is seldom considered in this context and is yet to be fully established.

2.4.2. Muscular strength and power

It is widely acknowledged that strength and power (particularly of the lower limbs) largely determine sprint start performance. Strength is typically defined as the peak force or torque produced during a maximal voluntary contraction (MVC), whereas power is the rate at which mechanical work is performed. The importance of these functional measures to performance are thought to differ greatly between athletic movements (Abernethy et al., 1995). In sprinting, relative power (i.e. the power-to-body mass ratio) is suggested to determine performance to a greater extent than maximum strength (Cronin and Hansen, 2005). Relative power relates to how explosively an athlete can move their body mass and is considered to be more directly applicable to the primary aim of sprint events (to cover a set distance in the shortest possible time). Nonetheless, these aspects of physical ability are not mutually exclusive (as power = force \times velocity) and both physical qualities are routinely monitored across a spectrum of sports.

Maximum strength can be assessed in several different ways, however, these traditionally include isometric, isokinetic and isoinertial strength tests. In contrast, ballistic measures (such as vertical jumps) are typically used to obtain information regarding maximum power capacity. These tests vary considerably in terms of the force-velocity and length-tension characteristics, which require careful consideration when attempting to implement monitoring protocols that are externally valid to the real performance context (Abernethy et al., 1995). The following sections will discuss the protocols used to obtain these different strength/power measures and the evidence surrounding their relationship to sprint start performance.

Isometric strength

An isometric MVC is the maximum force that can be exerted against an immovable object, with no joint angle changes and therefore, theoretically, no change in fascicle length during the contraction. Advocates of this testing argue that there is a very high level of control associated with these measures (Christ et al., 1994), whereas critics question the application to dynamic athletic situations (Murphy and Wilson, 1996). There have been few studies (Mero et al., 1983; Anderson et al., 1991; Kukolj et al., 1999) investigating the association between isometric strength and sprint performance. In a group of trained sprinters, with 100 m personal best (PB) times ranging from 10.2

to 11.8 s, strong relationships between relative isometric MVC of the knee extensors (knee angle = 107° and hip angle = 110°) and both block velocity and velocity at the 2.5 m mark ($r \pm 90\% \text{ CI} = 0.51 \pm 0.26$ and 0.60 ± 0.22 , respectively) were reported by Mero et al. (1983). Similarly, Anderson and colleagues (1991) reported a positive correlation between peak isometric hamstring force (30° knee flexion) and 40 yard sprint performance ($r \pm 90\% \text{ CI} = 0.40 \pm 0.23$). However, in contrast to these earlier studies, Kukolj et al. (1999) found unclear relationships ($r \pm 90\% \text{ CI}$ ranged from -0.12 ± 0.34 to 0.22 ± 0.33) between two sprint performance measures (0.5 – 15 m and 15 – 30 m average velocities) and maximum isometric forces of the hip extensors, hip flexors and knee extensors in physical education students. The differences in training status between the participants of the different studies, along with the variation in the joint angles and muscle groups assessed, may provide an explanation for these discrepancies. Overall, although there is some evidence for an association between isometric strength and sprint performance, the relationship is certainly not clear and this could be attributed to a lack of movement specificity (Murphy and Wilson, 1996).

Isokinetic strength

Isokinetic dynamometry measures the torque produced when the limb is moving at a constant angular velocity. This method requires sophisticated equipment which provides a tightly controlled setting and elicits a precise movement pattern through which the speed of the movement is fixed to a predetermined angular velocity and the torque applied to the dynamometer is quantified. However, similar to the isometric strength tests, isokinetic measurements have been criticised for lacking direct relevance to dynamic movements (Cronin et al., 2002). This is partly because the maximum concentric angular velocity for isokinetic devices is typically less than $450^\circ \cdot \text{s}^{-1}$, while many athletic movements have been shown to involve higher angular velocities (MacDougall et al., 1991). For example, peak angular velocities for three elite sprinters have been shown to exceed $450^\circ \cdot \text{s}^{-1}$ at the hip (from 474 to $525^\circ \cdot \text{s}^{-1}$), knee (from 456 to $526^\circ \cdot \text{s}^{-1}$) and ankle (from 583 to $725^\circ \cdot \text{s}^{-1}$) joints during the first stance phase (Bezodis et al., 2008). The external validity of isokinetic strength tests may be further questioned by the absence of angular accelerations and stretch shortening cycles which are present during sprinting, along with the lack of multiple-joint coordination.

Several studies have assessed the relationship between sprint performance and both concentric and eccentric measures of isokinetic strength (Alexander, 1989; Anderson et al., 1991; Nesser et al., 1996; Dowson et al., 1998; Manou et al., 2003). Higher concentric isokinetic strength measures (at the hip and knee joints) across a wide range of angular velocities ($30^{\circ}\cdot\text{s}^{-1}$ to $450^{\circ}\cdot\text{s}^{-1}$) tend to be related ($r \pm 90\%$ CI ranged from -0.35 ± 0.34 to -0.77 ± 0.30) to faster sprint times (Alexander, 1989; Anderson et al., 1991; Nesser et al., 1996; Dowson et al., 1998; Manou et al., 2003). Interestingly, these relationships between sprint performance and isokinetic strength appeared to be stronger at the faster angular velocities. For example, Nesser et al. (1996) found hip extension torque at $450^{\circ}\cdot\text{s}^{-1}$ to be more strongly related ($r \pm 90\%$ CI = -0.54 ± 0.28) to 40 m sprint time than at $180^{\circ}\cdot\text{s}^{-1}$ and $60^{\circ}\cdot\text{s}^{-1}$ ($r = -0.37 \pm 0.33$ and -0.28 ± 0.35 , respectively). Thus, isokinetic strength measures at faster movement velocities appear to be better predictors of sprint performance than those at slower velocities, perhaps supporting the need for velocity specific testing protocols. Additionally, Manou et al. (2003) demonstrated that concentric strength of the knee extensors was more strongly related to faster 30 m sprint time ($r \pm 90\%$ CI = -0.52 ± 0.30) than eccentric strength measures ($r = -0.30 \pm 0.40$) at the same angular velocity ($300^{\circ}\cdot\text{s}^{-1}$). This was perhaps an expected finding, as the acceleration phase has previously been shown to involve predominantly concentric muscle activity (Mero et al., 1983; Mero et al., 1992). Collectively, concentric isokinetic strength measures at high movement velocities seem to provide a valid indication of an individual's accelerative sprint ability.

Isoinertial strength

Isoinertial tests involve a constant resistance and are probably the most commonly employed method of strength testing in athletes, partly due to the accessibility of necessary equipment and familiarity of movements (Abernethy et al., 1995). This involves performing a dynamic exercise (often opposing the resistance of a weighted barbell) in which changes in muscle tension, length and contraction velocity are typically observed. Higher external validity is a clear advantage of isoinertial tests over isometric and isokinetic measurements. The requirement to control a free weight in these tests results in an arguably more relevant strength measure, as many athletic movements involve controlling a mass against gravity in multiple planes. Moreover, the inclusion of both concentric and eccentric contractions may be considered to further improve the external validity of this testing method to many sporting situations.

However, it is important to consider that many isoinertial tests require a high level of competency in order to adequately perform the movement with consistent technique and these tests may therefore be limited to the exercises that athletes are familiar with in training. Moreover, although the exercises commonly used for this type of testing are more dynamic than isometric tests, the speed of muscular contraction at near maximal forces is inherently slow. An additional criticism involves the emphasis on bilateral strength, whereas many functional performances (such as sprinting or the skeleton start) rely on unilateral strength and power as previously suggested (Markovic, 2007).

Despite these potential downfalls, Wisloff et al. (2004) reported a very strong relationship ($r \pm 90\% \text{ CI} = -0.94 \pm 0.06$) between higher one repetition maximum (1RM) half squat test and faster 10 m sprint times in elite male soccer players. Similarly, higher three repetition maximum power clean test results were associated with faster 10 and 40 m sprint times ($r \pm 90\% \text{ CI} = -0.56 \pm 0.27$ and -0.72 ± 0.20 , respectively) in professional rugby league players (Baker and Nance, 1999). Moreover, greater strength during front squat and power clean movements were associated with faster 20 m sprint times ($r \pm 90\% \text{ CI} = -0.60 \pm 0.21$ and -0.58 ± 0.21 , respectively) in Australian Rules football players (Hori et al., 2008). Importantly, in sprinters, faster 100 m sprint times have been related to and both higher 1RM squat ($r \pm 90\% \text{ CI} = -0.89 \pm 0.07$) in sprint-trained females (Meckel et al., 1995) and higher maximal force during a half-squat exercise ($r = -0.74 \pm 0.15$) in male sprinters (Bret et al., 2002).

Ballistic measures

When evaluating the relative advantages and disadvantages of isometric, isokinetic and maximum isoinertial strength testing methods, it becomes clear that these methods produce very different movements to the accelerative, high power and high velocity action observed in sprinting (Newton and Kraemer, 1994). For this reason, ballistic testing is often used to test the explosive capabilities of specific muscle groups. This involves maximally accelerating a mass in a specific direction until contact with the ground or equipment is lost. Therefore, these movements negate the period of deceleration which is observed in many isoinertial tests (Newton and Kraemer, 1994). Bench throws and some Olympic based lifts can be used, however, lower limb power is typically assessed through the use of vertical jump tests, most notably squat and countermovement jumps.

Squat jumps are often used as a concentric measure of explosive force production (Viitasalo and Bosco, 1982), which was previously found to be the dominant muscle action during the initial steps of a sprint (Mero, 1988). Therefore, it is perhaps unsurprising that squat jump height in sprinters positively correlates with block exit velocity ($r \pm 90\% \text{ CI} = 0.63 \pm 0.21$) and 2.5 m CM velocity ($r = 0.65 \pm 0.20$) in male sprinters (Mero et al., 1983). However, more recently, ten male sprinters (national and regional competitive level, mean PB \pm SD = 10.87 \pm 0.36 s) performed a series of squat jumps on a force plate, the traces of which were analysed for average and peak power, average and peak force, and jump height (Maulder et al., 2006). Interestingly, only certain squat jump outcome variables significantly correlated with 10 m sprint time ($r \pm 90\% \text{ CI} = -0.72 \pm 0.32$ and -0.73 ± 0.31 for average and peak power, respectively). It therefore appears that the ability to generate power during a squat jump provides a good indicator of 10 m sprint ability.

Countermovement jump tests are performed under similar conditions to the squat jump. However, countermovement jumps involve a downward countermovement phase immediately before the upward phase. This should result in a greater jump height than that during a squat jump due to the inclusion of a stretch shortening cycle and thus, information regarding elastic characteristics of the leg extensors can also be obtained (Bosco and Komi, 1980). When performed over a force plate, numerous force and power variables along with jump height can be analysed in a similar way to the squat jump tests. As shown in Table 2.2, a number of countermovement jump test variables are related to measures of sprint performance (Mero et al., 1983; Young et al., 1995; Kukolj et al., 1999; Bret et al., 2002; Liebermann and Katz, 2003; Maulder et al., 2006).

Table 2.2. Relationships between countermovement jump and sprint performance measures.

Study	Participants	Sprint performance measure	Countermovement jump measure	Correlation coefficient (<i>r</i>) (bars indicate \pm 90% CI)	
				-1.0	1.0
Mero et al. (1983)	25 male sprinters	Block velocity	Jump height		
		2.5 m velocity	Jump height		
Young et al. (1995)	11 male, 9 female sprinters	Time to reach 10 m	Jump height		
		Time to reach 2.5 m	Peak force		
Kukolj et al. (1999)	24 physical education students	0.5 – 15 m velocity	Jump height		
		15 – 30 m velocity	Jump height		
Bret et al. (2002)	19 male sprinters	0 – 30 m velocity	Jump height		
		30 – 60 m velocity	Jump height		
		60 – 100 m velocity	Jump height		
Liebermann and Katz (2003)	63 male, 43 female team sport athletes	Time to reach 20 m	Peak power		
Maulder et al. (2006)	10 male sprinters	Time to reach 10 m	Average power		
			Peak power		
			Average force		
			Peak force		

Central area ($r = 0.0 \pm 0.1$) indicates a trivial relationship

Vertical jump tests are probably the most commonly used by sports practitioners to assess power characteristics. However, it seems plausible that horizontal jump tests may also be valid indicators of sprint ability. Nesser et al. (1996) assessed the relationship between sprint performance and a five-step horizontal jump test, whereby the distance covered with five rapid, high velocity jumps was measured. The velocity of this movement and the length of contact phases were considered to mimic sprinting and higher jump distances were strongly related to faster 40 m sprint times ($r \pm 90\% \text{ CI} = -0.81 \pm 0.14$). Further, Mero et al. (1983) found standing triple jump distance to be positively related to 2.5 m velocity of the CM ($r \pm 90\% \text{ CI} = 0.66 \pm 0.20$) and block exit velocity ($r = 0.46 \pm 0.27$). However, unclear relationships have been observed between 10 m sprint performance and both a single leg hopping for distance test ($r \pm 90\% \text{ CI}$ were -0.23 ± 0.53 and -0.30 ± 0.52) and a single leg triple hopping for distance test ($r = -0.24 \pm 0.53$ and -0.33 ± 0.51) for the rear and front block legs, respectively (Maulder et al., 2006). Therefore, the relationship between horizontal jump measures and sprint start performance remains equivocal and vertical jump tests appear to be better predictors.

Reactive strength

Reactive strength is typically measured in situations where an athlete has a flight phase preceding a ground contact phase. The most common tests used to assess reactive strength are drop jumps, which typically involve an athlete dropping from a predetermined height onto a contact mat or force plate, before jumping for maximum height (Bosco and Komi, 1980). Athletes may be instructed to attempt to maximise jump height and minimise contact time, and the ratio between the height jumped and contact time is sometimes quantified (Young, 1995). In this way, drop jumps can be used as an indicator of fast reactive strength, with higher stretch loads compared with those associated with countermovement jumps (Bosco and Komi, 1980). Relatively few studies have assessed the relationship between drop jump test results and sprint performance (Mero et al., 1983; Young et al., 1995). Higher drop jump heights have been reported to be related ($r \pm 90\% \text{ CI} = 0.71 \pm 0.18$) to both higher block exit velocity and higher 2.5 m CM velocity in elite male sprinters (Mero et al., 1983). Additionally, drop jump height has been shown to differentiate performance levels in a group of nationally ranked female sprinters (Hennessy and Kilty, 2001) with higher drop jump heights associated with faster 30 m sprint times ($r \pm 90\% \text{ CI} = -0.79 \pm 0.17$).

Conversely, however, Young et al. (1995) found a very weak relationship ($r \pm 90\%$ CI = -0.09 ± 0.38) between drop jump performance (the ratio between jump height and contact time) and sprint start performance (2.5 m time) in Junior National track and field athletes. In fact, the best predictors of sprint start performance in the study conducted by Young et al. (1995) were all concentric measures, perhaps suggesting that reactive strength and the ability to utilise a stretch shortening cycle are less significant during the initial phases of acceleration for young, developing sprinters.

2.4.3. Flexibility

A further component of physical fitness which could be perceived to influence sprint start performance is flexibility which is typically defined as the range of motion around a joint or series of joints, and is primarily measured using static tests such as the sit and reach (Hubble-Kozey, 1991). Traditionally, flexibility was considered to be an important aspect of athletic performance, and for this reason, passive muscle stretching prior to training sessions and competitions was encouraged (Shellock and Prentice, 1985; Smith, 1994). Kinematic analyses have revealed superior sprint athletes to exhibit larger hip extension during the block phase (Bezodis et al., 2008; Bezodis et al., 2015) and first stance (Bezodis et al., 2008). However, this research by Bezodis et al. (2008; 2015) also found peak hip extension angles range from only 158 to 166° for the front leg at block exit and 160 to 165° for the rear leg at first stance toe-off. Additionally, Jacobs and van Ingen Schenau (1992) reported hip angles at second stance toe-off to be $172 \pm 3^\circ$ (mean \pm SEM). Thus, athletes do not appear to go into full hip extension during the initial acceleration phase and perhaps a lower range of motion should not be expected to limit sprint start performance. Indeed, Meckel et al. (1995) have observed unclear relationships ($r \pm 90\%$ CI = 0.17 ± 0.30) between sit and reach test scores and 100 m running time, demonstrating that these kinds of flexibility tests may not differentiate sprint performance level.

A potential explanation for these weak associations could be that flexibility during dynamic situations and the ability to produce high forces at the more extreme ranges of motion are perhaps more relevant to explosive performance than a static flexibility test. Alternatively, lower flexibility may indicate higher leg stiffness, an aspect considered to be important in sprinting (Bret et al., 2002). In fact, static stretching immediately prior to sprinting has been shown to be detrimental to performance (Nelson et al., 2005;

Winchester et al., 2008), perhaps due to a reduction in stiffness, energy recoil and thus, an increase in energy requirements. McNeal and Sands (2006) have therefore proposed that the relationship between flexibility and performance may be an optimisation (rather than a maximisation) issue.

2.5. Physiological adaptation to exercise and the implications for sprint start training

Several strength and power parameters were identified in the previous section (2.4) as important determinants of sprint start performance. Resistance training is widely accepted as an essential stimulus for muscular strength and power development, and is an integral component of sprint start training (Young, 2006). The following sections outline the neuromuscular adaptive responses to resistance training which contribute to strength and power development and discusses current findings surrounding the transfer of these adaptations to sprint performance.

2.5.1. Neuromuscular adaptation to training

Neuromuscular adaptations to different types of resistance training are well documented and are known to be specific to the training stimulus induced (Häkkinen, 1989; Aagaard et al., 2001; Ross et al., 2001; Aagaard et al., 2002a; Aagaard, 2003; Ahtiainen et al., 2003; Fry, 2004; Folland and Williams, 2007). Several studies (Kaneko et al., 1983; Moss et al., 1997; Toji et al., 1997; Toji and Kaneko, 2004; Cormie et al., 2007) have shown different types of training to elicit load-specific changes to the load-power curves. For example, Cormie et al. (2007) used squat jumps under a series of loads to illustrate this concept (Figure 2.2). Twelve weeks of training was conducted by 24 recreationally trained males, who were assigned to either the power (predominantly unloaded squat jumps), strength-power (90% 1RM squats combined with unloaded squat jumps) or control (no training conducted) group. Power training was shown to elicit training adaptation (jump height and power) at the low load and high velocity end of the spectrum, whereas strength-power training elicited increases in both of these jump performance outcomes across the entire load spectrum (Figure 2.2). As expected, the control group did not exhibit any changes in jump height, power or force across all five loads from the pre-test to post-test time points. This force-velocity specificity of adaptive responses to resistance training demonstrates the scope to manipulate neuromuscular adaptations through the alteration of training stimuli.

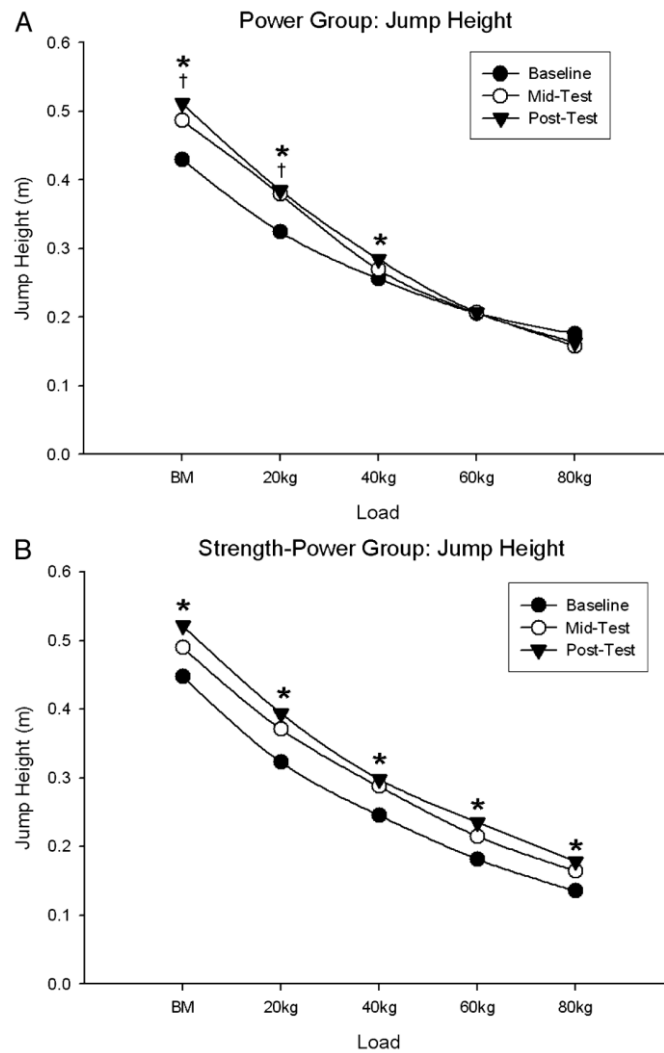


Figure 2.2. Maximal jump height achieved under each load by two groups across 12 weeks resistance training: (A) power and (B) strength-power based training groups (from Cormie et al., 2007). * denotes significant difference ($p < 0.05$) between baseline and post-testing; † denotes significant difference between baseline and mid-testing.

Aagaard (2003) summarised the typical adaptive responses to two discrete training types (Figure 2.3), illustrating the specific neuromuscular adaptations and the subsequent effects on functional outcome measures. According to this model, muscle hypertrophy training results in largely structural adaptation mechanisms, whereas explosive power training stimulates predominantly neural adaptation mechanisms. However, as illustrated in Figure 2.3, a crossover effect is believed to exist whereby some neural adaptations to hypertrophy training and some structural adaptations to explosive power training are exhibited. Both structural and neural adaptation

mechanisms have roles in the enhancement of muscular strength, primarily through increases in the number of sarcomeres (and thus, cross-bridges) in series and enhanced neural activation of motor units, respectively. Additionally, these neural adaptations have been implicated in the resistance exercise-induced improvements in explosive muscle strength, rate of force development and eccentric muscle strength (Figure 2.3).

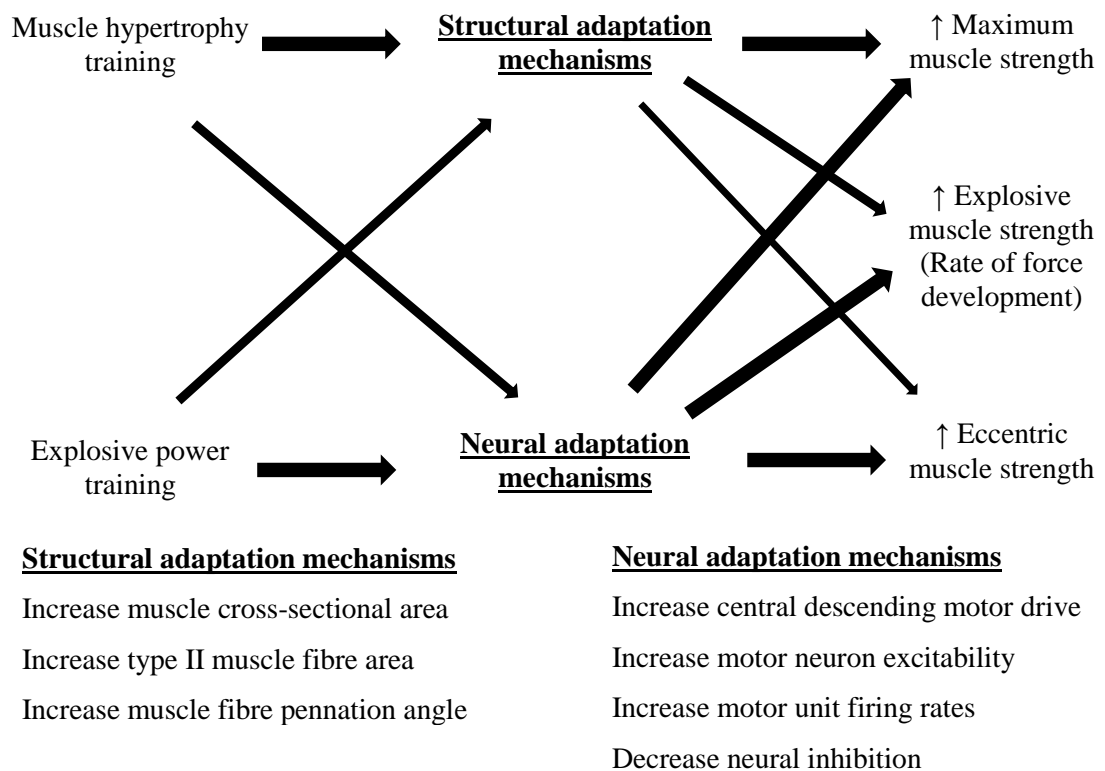


Figure 2.3. Structural and neural adaptations to strength training. Thick arrows represent strong associations and thin arrows represent weaker associations. Adapted from Aagaard (2003).

Structural adaptations to training

An increase in muscle mass and contractile strength is a widely documented response to heavy resistance training (Jones et al., 1989; Staron et al., 1990; Ahtiainen et al., 2003). This can be predominantly attributed to an increase in the size of muscle fibres (hypertrophy) through the stimulation of protein synthesis (Bhasin et al., 2001b) and proliferation of satellite cells (Folland and Williams, 2007). Additionally, an increase in pennation angle can also be observed following resistance training which is associated with an increase in the physiological cross sectional area, the number of force-bearing

cross bridges and thus, maximum strength (Aagaard et al., 2001). Although hyperplasia (an increase in the number of muscle fibres) could increase whole muscle cross-sectional area, limited evidence exists for this process in human skeletal muscle (Kelley, 1996).

Preferential hypertrophy of the type II muscle fibres is commonly reported following resistance training (Tesch, 1988; Staron et al., 1990) with the degree of hypertrophy largely dependent on the relative loading of the muscle (Fry, 2004). As the ability of a muscle to contract quickly and forcefully is related to the number and size of fast twitch (type II) muscle fibres (Thorstensson et al., 1976), training for sprint-based athletes is typically geared towards selective hypertrophy of these type II fibres. Indeed, a six week sprint training programme which resulted in significant increases in sprint performance (time to 40 m), was also found to significantly increase the area ($57.0 \pm 6.6\%$ to $65.6 \pm 4.0\%$; mean \pm SE) of type II fibres (Dawson et al., 1998).

Combinations of the three main myosin heavy chain isoforms are known to occur within a single skeletal muscle fibre and result in a continuum of hybrid fibre types (Pette, 2001). During a period of training adaptation, the amount of hybrid fibres in 'transforming' muscle increases due to the coexistence of different myosin heavy chain isoforms in response to a specific training stimulus (Pette and Staron, 1997). Interestingly, heavy resistance training seems to suppress the expression of the fastest myosin heavy chain IIX and concomitantly stimulates the expression of type IIA (Adams et al., 1993; Andersen and Aagaard, 2000). In contrast, slow twitch (type I) fibres appear to be largely unaffected by heavy resistance training (Aagaard and Andersen, 1998; Bottinelli et al., 1999). Conversely, cessation of resistance training appears to increase the expression of type IIX fibres and decrease the expression of type IIA (Andersen and Aagaard, 2000). Thus, it appears that transitions between the myosin heavy chain isoforms are possible under certain circumstances, specifically between fast fibre subtypes (Fry, 2004; Folland and Williams, 2007). It may be expected that the apparent slowing of muscle fibres (IIX \rightarrow IIA) induced by resistance training could be unfavourable to sprint based events. However, this is more than outweighed by the increase in muscular strength and power as a result of type IIA fibre hypertrophy (Aagaard, 2004).

Neural adaptations to training

The second branch of adaptation to training relates to neural factors (Figure 2.3) and includes the activation and coordination of skeletal muscle which supplement the structural adaptations to result in further improvements in force production (Aagaard, 2003). In fact, during the initial stages of strength training, neural enhancements are believed to be responsible for strength gains (Moritani and deVries, 1979; Häkkinen, 1989; Häkkinen et al., 1990; Aagaard et al., 2002a), with increases in maximal strength observed in the absence of hypertrophy (Häkkinen, 1989; Gabriel et al., 2006). Thereafter, improvements in maximum strength are predominantly associated with a gradual increase in muscular hypertrophy (Moritani and deVries, 1979). Neural changes include increases in motor unit recruitment, firing frequency, motor neuron excitability and reduction in descending inhibitory pathways, which contribute to gains in maximal muscle strength, increased rate of force development and maximal eccentric muscle strength (Figure 2.3). Neural adaptations have been measured using electromyography (Moritani and deVries, 1979; Häkkinen et al., 1985a; Häkkinen et al., 1985b; Aagaard et al., 2002a), muscle twitch measures (van Cutsem et al., 1998) and spinal reflex measurements (Aagaard et al., 2002b). However, in the practical setting, these adaptive responses to training are most commonly assessed indirectly through physical function measures which are associated with adaptation of the nervous system. For example, improvements in the maximum rate of force development (particularly without an increase in maximum force) are thought to reflect enhancements in neural activation in trained individuals (Aagaard, 2003).

The role of hormones in training adaptation

Hormonal responses to exercise are well documented (Häkkinen and Pakarinen, 1993; Ahtiainen et al., 2004; Kraemer and Ratamess, 2005; Linnamo et al., 2005; Smith et al., 2013; Stokes et al., 2013) and are considered necessary stimuli for neuromuscular adaptation to take place (Häkkinen, 1989; Crewther et al., 2006). Testosterone and cortisol are traditionally considered to be key endocrine markers in the training process, primarily for their purported involvement in muscular hypertrophy (Bhasin et al., 2001b; Viru and Viru, 2004). Several studies have proposed a link between testosterone and both the accrual of lean mass and associated strength improvements (McCall et al., 1999; Ahtiainen et al., 2003; Beaven et al., 2008a; Rønnestad et al., 2011). This has contributed to the dose-response paradigm that larger testosterone responses to exercise

will result in greater training-induced adaptations, with testosterone-modulated increases in protein synthesis proposed as the primary mechanism (Bhasin et al., 2001a). Beaven et al. (2008a) presented some evidence that functional gains can be maximised through the prescription of training which elicits a more ‘anabolic’ milieu for individual rugby players. However, this dose-dependent relationship between testosterone and adaptation has been more recently challenged, and training-induced elevations in testosterone have been found to enhance neither myofibrillar protein synthesis (West et al., 2009) nor muscle hypertrophy and strength (West et al., 2010) of the elbow flexors. Although not fully elucidated, it has been suggested that testosterone may have a more permissive role in training adaptation, with local factors (e.g. satellite cell proliferation; Bellamy et al., 2014) responsible for hypertrophy.

As shown in Figure 2.4, testosterone and cortisol have been proposed to have both long-term (genomic) and short-term (non-genomic) actions on the central and peripheral nervous systems (Crewther et al., 2011).

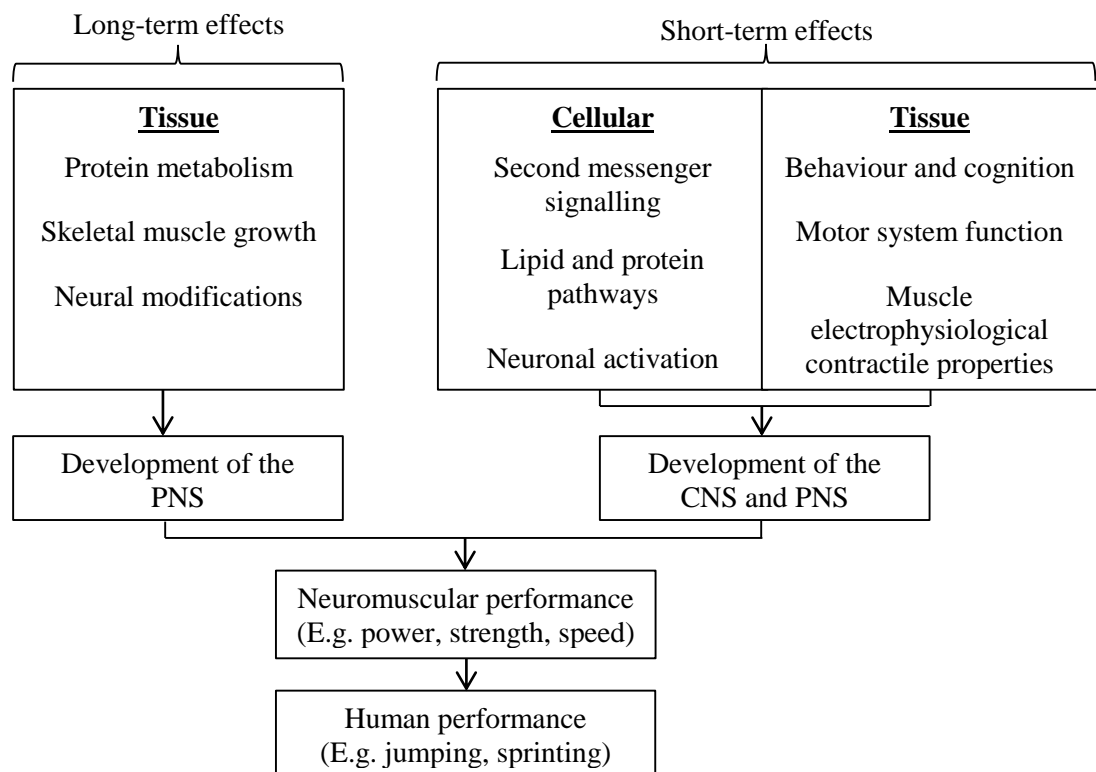


Figure 2.4. The dual-effects of testosterone and cortisol on the neuromuscular system and the performance implications (from Crewther et al., 2011). CNS = central nervous system. PNS = peripheral nervous system.

Testosterone and cortisol have been reported to induce rapid changes in neuronal activity in animals (Chen et al., 1991; Smith et al., 2002) and human mood and behaviour (Book et al., 2001), and to modulate calcium influx in muscle cells (Estrada et al., 2003). The previously reported associations between testosterone and the short-term expression of explosive performance (Bosco et al., 1996a; Bosco et al., 1996b; Cardinale and Stone, 2006; Crewther et al., 2009) could be attributed to the above rapid mechanisms. Thus, it has been suggested that regular hormonal monitoring may provide an indication of adaptation to training programmes which are intended to enhance explosive performance (Cardinale and Stone, 2006).

The behavioural effects of testosterone are suggested to have potentially important implications for athletic training with strong relationships (r ranged from 0.67 to 0.83) reported between free testosterone and self-selected training load in elite female netball players (Cook and Beaven, 2013) and elite male rugby union players (Cook et al., 2013). Moreover, Cook and Crewther (2012) used motivational video clips to elevate serum testosterone in elite male rugby players and observed subsequent workout performance to be enhanced. Thus, it is hypothesised that athletes with elevated testosterone levels are more motivated to train with heavier loads. Theoretically, the small differences in training stimulus of each session could accumulate over the course of a training season to result in a greater training stimulus, and thus, potentially superior neuromuscular adaptation. This may provide an alternative pathway through which testosterone regulates adaptive training responses and could be responsible in part for the previous association between testosterone and lean mass accrual across a training season (Ahtiainen et al., 2003).

In recent times, evidence has implicated dihydrotestosterone (DHT, a metabolite of testosterone) as a potentially more potent anabolic stimulus than testosterone itself (Bauer et al., 2000; Hamdi and Mutungi, 2011; Yarrow et al., 2012). Additionally, Hamdi and Mutungi (2010) have reported non-genomic effects of DHT with enhanced isometric force in fast twitch muscle fibres when isolated muscle fibre bundles from mice were perfused with this hormone. The expression of the enzyme 5 α -reductase, which is necessary for the conversion of testosterone to DHT, was previously considered to be insufficient in human skeletal muscle (Thigpen et al., 1993). However, the recently discovered type 3 5 α -reductase isoform (Godoy et al., 2011) along with the

observed responses of DHT to sprint exercise (Smith et al., 2013) has generated new interest and speculation surrounding its role in athletic performance. More research is required before the functional significance of the DHT response to different exercise stimuli is elucidated.

2.5.2. Resistance training and sprint start performance

The transfer of strength and power development to sprint start performance

Several physical determinants of sprint start performance were outlined in section 2.4 along with the measurement techniques typically adopted. However, the relationships between sprint performance and strength and power indices do not indicate causality, and a direct link between strength and power gains and improvements in sprint start performance does not necessarily exist. In fact, heavy resistance leg extensor exercise has previously been shown to be an effective method in which to enhance maximum squat strength in trained individuals, but this failed to transfer to an improvement in sprint velocity (Wilson et al., 1993; Harris et al., 2000). Conversely, Wilson et al. (1996) later reported a positive relationship ($r \pm 90\%$ CI = 0.30 ± 0.30) between improvements in 1RM squat exercise and 40 m sprint performance in trained male students.

As lower limb power appears to be more strongly related to sprint performance than strength, it may be expected that changes in lower limb power are more likely to correlate with sprint performance enhancement. Previously, substantial gains in lower limb power have been reported following eight weeks of high power training involving jump squat or plyometric exercises, however this did not appear to significantly influence sprint performance (Harris et al., 2000; McBride et al., 2002). On the other hand, a study conducted by Wilson et al. (1993) found a 10 week training programme involving squat jumps (weighted to maximise power output) to significantly improve both squat jump height and 30 m sprint time in previously trained individuals. Overall, the relationships between strength and power development and sprint performance enhancements remain equivocal and thus, the prescription of resistance training to improve sprint performance appears to be more complex than simply developing strength and/or power.

Sprint start training methods

Remarkably few studies have assessed the efficacy of different types of resistance training to enhance sprint performance. This gap in the literature is perhaps due to a lack of access to truly elite athletes, the difficulties involved in quantifying training load, and the potential reluctance of athletes and coaches to participate in strictly controlled training studies (Kearney, 1999). Rimmer and Sleivert (2000) have found an eight week plyometric training block to elicit similar improvements in 10 and 40 m sprint times as a sprint-only training block in a group of healthy males. However, less trained individuals are known to adapt more quickly (Häkkinen, 1985) and to a wider range of stimuli (Fleck, 1999) than those with more extensive training histories, perhaps limiting the application of these findings to elite sprinters.

To the author's knowledge, only one study (Blazeovich and Jenkins, 2002) has assessed the effect of different training stimuli on sprint performance in well-trained sprinters. Ten nationally ranked junior sprinters (mean 100 m PB \pm SD = 10.89 \pm 0.21 s) underwent a seven week training intervention whereby participants completed either a high-velocity (light resistance) or low-velocity (high resistance) programme alongside their normal sprint training. Although 20 m sprint acceleration performance was improved in both groups, no velocity specific training adaptations were reported in response to high vs. low velocity training programmes. Therefore, it appears that different types of resistance training, when undertaken concurrently with sprint training, are able to elicit similar improvements in accelerative sprint performance. This is perhaps due to the inclusion of sport-specific exercises, as it has been suggested that the transfer of structural adaptations to enhanced sprint running performance may be delayed (Moir et al., 2007) and require the 'conversion' of muscular strength and/or power to a coordinated sports skill (Young, 2006). The proposed importance of including specific exercises to improve intermuscular coordination, may somewhat explain the unclear relationships between strength and power gains and sprint performance enhancements in the training studies (section 2.5.2).

It is widely accepted that careful periodisation of training programmes can contribute to greater training adaptations (Fleck, 1999). In order to enhance explosive performance, it has been suggested that training emphasis in the early stages of a training season should be generalised for maximum strength development, with later training cycles focussed

on higher velocity, sport-specific exercises (Baker, 1996). Indeed, this sequenced combination of training has been shown to elicit greater improvements in lower limb power and accelerative sprint performance than both high force and high power training alone, in university level American football players (Harris et al., 2000). However, to the author's knowledge, no studies have assessed the efficacy of different combinations of resistance training to performance in elite sprinters (or skeleton athletes).

Monitoring adaptations to training

The previous section outlined the evidence surrounding the use of resistance training to enhance sprint performance and introduced the need for complex programming and periodisation of training programmes to elicit sprint performance enhancements. In order to accurately assess adaptation across each of these training blocks and overall training progress, a carefully scheduled monitoring programme based on valid and reliable monitoring protocols is considered essential (Newton et al., 2011). Several physical tests were outlined in section 2.4, the scores of which have been shown to relate to sprint start performance and thus, may provide a valid indication of the training progress in sprinters and perhaps skeleton athletes. Coaches and sport scientists can use the objective information obtained from these tests to evaluate and optimise their training strategies, rather than relying on anecdotal evidence. However, physical tests are likely to overlap in terms of the physical characteristic being measured. Thus, the use of multifactorial analysis of the task has previously been recommended to improve the efficiency of testing batteries and to ultimately improve training practices (Cronin and Hansen, 2005). Additionally, to ensure that meaningful data are obtained from this type of testing, it is important to restrict as many confounding factors as possible (Newton et al., 2011). Tightly controlled, research-based protocols are difficult to implement in the applied athletic setting but could enable the collection of much needed scientific evidence to inform the training process. These factors include (but are not limited to) controlling warm-up protocols and restricting physical activity in the preceding 48 hour period to ensure athletes enter the testing sessions in a similar physiological state (Newton et al., 2011).

Biochemical monitoring, alongside the more conventional physical tests, has been suggested to provide additional insight into the effects of training (McGuigan and Cormack, 2011). In particular, the emergence of short-term mechanisms of testosterone

and the associations between baseline testosterone and explosive performance (discussed previously in section 2.5.1) have resulted in suggestions that testosterone should be routinely monitored to obtain insight into the adaptive responses to training (Cardinale and Stone, 2006). An athlete's hormonal status can be regularly monitored using either blood or salivary samples and the results obtained using these two methods appear to largely agree (Wang et al., 1981; Neary et al., 2002). The relative advantages and disadvantages of each must therefore be considered with respect to the individual testing environment (McGuigan and Cormack, 2011). For example, venous samples are not appropriate outside of the laboratory setting and saliva samples (which may provide a more practical, non-invasive measure) may be contaminated by food and drink intake. Careful storage and analysis also appear to be important (Toone et al., 2013) and samples should be collected at a consistent time of day due to the known circadian rhythm of hormones (Dabbs, 1990; Aubets and Segura, 1995).

Muscle damage has been associated with increased muscle soreness and acute reductions in muscular functional capacity (Clarkson et al., 1992). Thus, an important consideration when monitoring athletes, and attempting to obtain insight into neuromuscular adaptation, is that the level of muscle damage is not excessive and/or is consistent between measurement time-points. Serum concentrations of several muscle proteins can provide an indirect measure of myocyte damage (Clarkson and Hubal, 2002). Creatine kinase (CK) is perhaps the most readily used biomarker in the literature, probably due to the magnitude of the response to eccentric exercise and the relatively inexpensive assay. Although the volume of eccentric exercise has been shown to induce increases in CK and greater levels muscle soreness (Clarkson and Tremblay, 1988), weak correlations have been reported between CK concentrations and muscle soreness at a group level (Rodenburg et al., 1993; Nosaka et al., 2002). However, the large inter-individual variation in the CK responses to the same exercise stimulus (Clarkson and Hubal, 2002), along with the subjective nature of muscle soreness reporting (Nosaka et al., 2002), may be somewhat accountable for this discrepancy. Longitudinal analysis concerning how CK responses and muscle soreness covary within-individuals would further the understanding of this association.

Training status is known to influence the CK response to an eccentric exercise stimulus, with trained individuals exhibiting a smaller increase in serum CK, attenuated loss of

strength and faster recovery of this strength deficit than less trained individuals in response to strenuous eccentric exercise of the elbow flexors (Newton et al., 2008). This finding is somewhat attributable to a phenomenon known as the 'repeated-bout effect' which relates to a protective effect that one exercise session has on subsequent bouts (Clarkson et al., 1992) and results in resistance to muscle damage for several months depending on the muscle damage initially induced (Nosaka et al., 2001). The longitudinal monitoring of the CK response to the same exercise stimulus may therefore be used, in conjunction with physical performance tests, to provide additional detail when evaluating training status.

2.6. Biomechanics of sprint start performance

Like all sporting scenarios, sprint start performance is not only determined by physical abilities, but psychological and biomechanical factors also have key roles (Smith, 2003). Although differences between the start phase in sprinting and skeleton are clear, some research findings surrounding the biomechanical determinants of sprint start performance could be somewhat translated into the context of skeleton and used to guide the initial stages of this research. Sprinters must not only have the ability to accelerate their body mass from a stationary position, but also must be able to apply high forces to the ground whilst moving at very high velocity. Thus, Delecluse (1997) suggested that sprinting should be viewed as a multidimensional skill, consisting of different phases which have unique physical and technical requirements. For the purposes of this review, the sprint start will be divided into the block phase and acceleration phase (from block exit to maximum velocity attainment). The following sections will firstly discuss the different performance measures which have previously been used to quantify sprint start performance and their relevance to skeleton start performance. A review of the pertinent literature surrounding the biomechanical determinants of the block and acceleration phases will then follow.

2.6.1. Sprint start performance measures

Block exit velocity is perhaps the most frequently used measure of block phase performance (Vagenas and Hoshizaki, 1986; Mero, 1988; Guissard et al., 1992; Schot and Knutzen, 1992; Mendoza and Schöllhorn, 1993; Mero et al., 2006). Van Coppenolle et al. (1989) reported block exit velocities ranging from 3.80 to 3.94 m·s⁻¹ in highly

skilled sprinters (100 m PB times ranging from 10.02 to 10.22 s). Conversely, less skilled sprinters (100 m PB times 10.39 to 11.60 s) have typically exhibited lower block exit velocities ranging from 2.97 to 3.83 m·s⁻¹ (Mero, 1988; van Coppenolle et al., 1989; Mero and Komi, 1990; Bezodis et al., 2010). Although block exit velocity seems to differentiate performance levels amongst sprinters, this performance measure has been shown to be flawed in this context (Mendoza and Schöllhorn, 1993; Bezodis et al., 2010). For sprinters to exit the block with higher horizontal velocity, an increase in horizontal impulse must occur, requiring a greater amount of force exerted against the block and/or a longer duration of time that force is exerted for. If the latter strategy is adopted (time spent on the block is increased) the primary aim of sprint events (to cover a set distance in the least time possible) is opposed. Thus, in athletic sprint starting, it is unclear whether superior start performances are those in which the athlete maximised block exit velocity or reduced block exit time.

Several studies have used the time taken to reach a fixed distance (Henry, 1952; Vagenas and Hoshizaki, 1986; Schot and Knutzen, 1992; Mendoza and Schöllhorn, 1993; Mero et al., 2006) and instantaneous velocities at set distances (Schot and Knutzen, 1992; Salo and Bezodis, 2004) to quantify sprint start performance. However, Bezodis et al. (2010) illustrated that these different performance measures provide conflicting assessments of performance, and as originally suggested by van Coppenolle et al. (1989), a single measure of sprint start performance should incorporate both velocity and temporal measures. To this end, horizontal block acceleration (van Coppenolle et al., 1989) and normalised horizontal external power (Bezodis et al., 2010) have been used to provide more appropriate measures of block phase performance. In both studies, more skilled sprinters were typically found to produce greater horizontal external power and block acceleration than their less skilled counterparts. For example, Bezodis et al. (2010) reported that the most skilled sprinter (100 m PB = 10.53 s) produced a normalised average horizontal external block power of 0.63 ± 0.04 (mean \pm SD), compared with 0.41 ± 0.02 for the least skilled sprinter (100 m PB = 11.6 s), across three maximal effort sprint starts.

In skeleton, however, the timing system does not begin until the photocell beam at the 15 m mark has been interrupted. Therefore, the amount of time an athlete spends pushing against the block does not directly impair performance in the same way as in

athletics and high block exit velocity is desirable, regardless of the potential increase in block time. For the same reason, time to the 15 m mark is also an irrelevant measure of performance and velocity at the 15 m mark may, in fact, provide a better indication of performance across this section of the track. Thereafter, once timing is initiated at the 15 m mark, the same principles apply to skeleton and athletic sprint starts, and both time and velocity components should be integrated into a single performance measure of this discrete phase. A challenge, therefore, is to formulate a measure of skeleton start success which accurately reflects and objectively quantifies the success of the entire start phase, from the block through to the 65 m mark (the end of the start phase).

2.6.2. Block phase

With consideration of the above issues, the following sections will outline the kinematic and kinetic determinants of block phase performance in athletic sprinting which are relevant to skeleton start performance.

Kinematic determinants of block phase performance

To investigate whether an optimum block set-up exists, the effect of adjusting block spacing has been previously studied. Three types of start have typically been investigated: bunched, medium and elongated (relating to the longitudinal distances between the feet; 25-30, 40-50 and 60-70 cm, respectively). Henry (1952) found increases in the spacing between blocks to be associated with increases in both block exit velocity and block time. As previously discussed, an increase in block time opposes the primary aim in sprinting and it has therefore been concluded that medium block spacing may provide an optimum balance between block time and block exit velocity (Henry, 1952; Schot and Knutzen, 1992). Conversely, the increase in block time associated with an elongated start is not detrimental to skeleton start performance (previously described in section 2.6.1). Thus, while these findings cannot be directly transferred to the skeleton start *per se*, it may be worth considering a more elongated foot position on the skeleton start block in an attempt to generate greater impulse on the block and thus, maximise starting velocity.

Bezodis et al. (2015) investigated joint kinematics across the block phase in three male elite sprinters (European Indoor 60 m finalists; 100 m PB times ranged from 9.98 to 10.51 s). The most skilled sprinter was found to exhibit larger hip and knee extension

range, as well as higher average hip extension velocities, compared with the slower sprinters. It was therefore concluded that an increased contribution from the hip extensors, particularly of the rear hip in early block phase, may benefit elite sprinters during the block phase. Differences in running posture between skeleton and athletic sprint starts clearly exist and the scope for skeleton athletes to extend these lower limb joints may be limited to some extent. Nonetheless, it is conceivable that greater positive work generated by the hip and knee extensors across a greater range of extension would also benefit skeleton athletes. In this case, skeleton start training should perhaps be tailored to target these specific muscle groups and actions.

Kinetic determinants of block phase performance

In an attempt to build on the knowledge regarding kinematics during the block phase and develop an understanding for the causes of the movement, kinetic determinants of performance have been extensively investigated. Many have combined the forces produced at the front and rear block to report the horizontal, vertical and/or resultant force components throughout the block phase. Using these force traces, several studies have reported horizontal impulse and block time (Baumann, 1976; Mero et al., 1983; Slawinski et al., 2010), and horizontal block exit velocity (Baumann, 1976; Slawinski et al., 2010) for groups of varying sprint ability. Table 2.3 summarises these findings.

Table 2.3. Sprint performance and kinetic variables (mean \pm SD) for elite and sub-elite sprinters during the block phase of a sprint start.

Study	100 m PB (s)	No. of participants	Horizontal impulse (Ns)	Horizontal block velocity ($\text{m}\cdot\text{s}^{-1}$)	Block time (s)
Baumann (1976)	10.35 ± 0.12	12	263 ± 22	3.6 ± 0.2	0.47 ± 0.04
	11.11 ± 0.16	8	223 ± 20	3.1 ± 0.2	0.47 ± 0.02
	11.60 ± 0.24	10	214 ± 20	2.9 ± 0.2	0.50 ± 0.03
Mero et al. (1983)	10.8 ± 0.3	8	$234 \pm 15^{**}$	-	0.36 ± 0.03
	10.8 ± 0.4	9	$226 \pm 31^*$	-	0.36 ± 0.02
	11.5 ± 0.3	8	195 ± 23	-	0.37 ± 0.04
Slawinski et al. (2010)	10.27 ± 0.14	6	$276 \pm 36^*$	$3.48 \pm 0.05^*$	0.35 ± 0.02
	11.31 ± 0.28	6	215 ± 29	3.24 ± 0.18	0.35 ± 0.02

* denotes significantly ($p < 0.05$) higher than the slower group (within the study).

** denotes significantly ($p < 0.001$) higher than the slowest group (within the study).

N.B. Baumann (1976) did not report statistical significance.

Faster sprinters (100 m PB times) consistently generated greater horizontal impulses and attained higher block exit velocities, than their slower counterparts. Further, each of the studies reported similar block times (or push duration) between elite and sub-elite groups. It therefore appears that elite sprinters are able to produce significantly greater impulses on the blocks than their sub-elite counterparts, by exerting greater forces (relative to body mass) rather than increasing push-off duration from the blocks. Similarly, in swimming, Vantorre et al. (2010) found elite front crawl swimmers to produce significantly ($p < 0.05$) greater horizontal impulses than trained swimmers (208.8 ± 21.1 and 150.3 ± 39.5 Ns, respectively; mean \pm SD) over a significantly shorter period of time than the trained group (0.73 ± 0.07 and 0.78 ± 0.05 s, respectively). Therefore, in line with the evidence from athletic sprinting, skilled swimmers appear to be able to increase horizontal impulse production by increasing the amount of force they apply to the blocks, rather than the time on the blocks. However, as the arm contribution to swimming starts have been shown to account for as much as one-third of the total impulse during track starts (Breed and McElroy, 2000), direct comparisons across sports may be complicated. Nonetheless, it is plausible that these findings translate into the context of the skeleton start to some extent. It is likely that faster starters in skeleton are those athletes who are able to produce greater force in the same period of time than their slower counterparts, and consequently produce greater impulse against the block to exit with higher velocity. As competition timing does not begin until the 15 m mark in skeleton, a potential strategy to improve block phase performance without necessarily advancing physical capacity could be to spend a longer period of time exerting force against the block (as discussed in section 2.6.1). This could increase horizontal impulse (and thus, velocity) without negatively impacting performance.

Other studies have used two separate force plates or strain gauges to investigate the forces applied to each block in sprinting. Guissard and Duchateau (1990) examined the force-time curves produced by seven male sprinters (100 m PBs ranged from 10.8 to 11.2 s) during the block phase. Larger peak forces were produced on the rear compared with the front block, however, horizontal impulse was considerably smaller for the rear block (61.0 ± 11.9 compared with 190.1 ± 48.8 Ns on the front block; mean \pm SD). This can be attributed to the fact that the duration of force application on the front block was over twice that of the rear. To investigate whether leg placement was therefore an important factor for performance, Vagenas and Hoshizaki (1986) assessed the dynamic

strength of 15 skilled sprinters using a single-leg vertical jump test and determined each athletes dominant limb. Significantly greater mean block velocities were reported when the stronger leg, compared with the weaker leg, was placed on the front block (3.37 and 3.12 m·s⁻¹, respectively; $p < 0.05$). Consequently, placing the stronger leg on the front block was suggested to enhance performance on the starting blocks. However, the implications of this for force production during the first and subsequent stance phases were not considered and the overall effect of these interventions on sprint performance remains unclear.

From the above findings, it could be interpreted that the forces applied to the front block are more crucial determinants of sprint performance than those applied to the rear. However, studies have shown that, in fact, the peak rear block forces are significantly greater in skilled sprinters than less skilled sprinters (van Coppenolle et al., 1989; Harland and Steele, 1997; Fortier et al., 2005). Moreover, it has been suggested that more skilled sprinters may even produce less force on the front block, than slower sprinters (van Coppenolle et al., 1989; Fortier et al., 2005). For example, van Coppenolle (1989) recorded greater rear block forces (1487 N) for a 100 m World Championships finalist (100 m PB = 10.22 s) compared with a national level sprinter (442 N; 100 m PB = 10.39 s). On the front foot, however, the national sprinter produced greater forces than the World Championship finalist (981 compared with 774 N, respectively). It therefore seems as though the ability to produce large forces across shorter push durations on the rear block could differentiate sprint performance levels. Skeleton athletes typically start with one foot in contact with the block and one foot on the ice, however athletes may start with both feet on the block if preferred. The difference in the amount of force that is produced by the front and rear legs in skeleton may be greater than in sprinting as a result of the lower coefficient of friction between the front foot and the ice, in comparison with rear foot pushing against the wooden block. Therefore, it seems possible that the high importance of rear leg force production observed in athletic sprint starts could be even greater for skeleton starts on ice-tracks, although this is yet to be investigated.

2.6.3. Acceleration phase

Although variation in the velocity-time profiles across the acceleration phase of sprinting exists (Volkov and Lapin, 1979; Moravec et al., 1988; van Coppenolle et al.,

1989), maximum speed is typically reached 4-5 seconds or 30-60 metres into a sprint (Volkov and Lapin, 1979; Moravec et al., 1988). More rapid accelerations can be associated with reduced time spent at submaximal velocities, higher average velocities and therefore, faster sprint times (van Ingen Schenau et al., 1991; de Koning et al., 1992; van Ingen Schenau et al., 1994). The following sections outline the scientific evidence relating to the kinematics and kinetics during the acceleration phase of the sprint start and discuss the potential application to skeleton start performance.

Kinematic determinants of acceleration phase performance

Several kinematic variables have been reported for international sprinters during the initial steps of the acceleration phase (Atwater, 1982; Salo et al., 2005). Atwater (1982) found mean step lengths to increase across the four steps (1.01, 1.13, 1.33 and 1.47 m, respectively), whereas mean stance duration decreased across the first three contact phases after block exit (0.194, 0.181 and 0.165 s, respectively). These findings have since been reinforced by Salo et al. (2005), whereby contact times were found to decrease and flight times increase for a male sprinter (PB = 10.80 s) across the first four steps (flight phase from block exit to first contact was excluded). Thus, the amount of time available to the exert force against the ground and accelerate the CM reduces across the initial steps of the acceleration phase. Salo et al. (2005) also reported an increase in horizontal velocity drop across the first four stance phases (-0.02 ± 0.01 , -0.04 ± 0.01 , -0.04 ± 0.00 and $-0.06 \pm 0.02 \text{ m}\cdot\text{s}^{-1}$, respectively) in a skilled sprinter (100 m PB = 10.80 s). However, faster sprinters (100 m PB = 10.8 ± 0.4 s; mean \pm SD) have been found to exhibit less horizontal deceleration than slower sprinters (100 m PB = 11.5 ± 0.3 s) during both the first (3.0 vs. 11.3%, respectively) and second (3.6 vs. 8.8%, respectively) contact phases (Mero et al., 1983). Thus, to attain higher performance levels during the initial acceleration phases, sprinters should strive to reduce the horizontal deceleration of the CM during stance (potential mechanisms for this will be discussed in the next section).

Bezodis et al. (2008) analysed the joint kinematics of three male sprinters (100 m PB = 9.98, 10.22 and 10.51 s) during the first stance phase and reported that, following an initial ankle dorsiflexion, all three sprinters extended the stance leg continuously during the first stance phase. The fastest (based on 100 m PB) and most powerful (based on horizontal normalised power during first step) sprinter was found to exhibit a greater

range of extension compared with the slowest and least powerful sprinter at both the hip (70 vs. 61°, respectively) and the knee (53 vs. 35°, respectively) during the first stance. Moreover, the most skilled sprinter exhibited a higher total range of leg extension than his slower counterparts (160 vs. 144 and 137°, respectively). Therefore, a higher range of lower limb joint extension appears to be favourable during the first stance phase. In skeleton, the range of extension that skeleton athletes can achieve may be more limited than in athletic sprint starts due to the requirement to maintain contact with, and push, the sled in a bent-over position. Nonetheless, it seems plausible that maximising extensor work at the hip and knee joints could be associated with superior skeleton start performance. Skeleton start training should, therefore, incorporate exercises which include powerful extension of the hip and knee joints. Additionally, physical tests to assess the capabilities of the hip and knee extensors may provide insight into the development of skeleton athletes.

Kinetic determinants of acceleration phase performance

The ground reaction forces and impulses exerted during stance phases of sprinting are often considered in two distinct phases: the braking phase and the propulsive phase (Mero et al., 1983; Mero, 1988; Salo et al., 2005). These are based on the direction of the ground reaction force vector, with braking forces representing negative forces and propulsive forces representing positive forces in the anterior-posterior direction. The acceleration phase is characterised by positive net horizontal impulses (the sum of the braking and propulsive impulses) produced during stance and thus, an increase in horizontal velocity. At the point of maximum velocity attainment, net impulses are very close to zero (however may be slightly positive in order to overcome air resistance) and there is no change in overall velocity.

On leaving the blocks, a sprinter must prepare for the first ground contact in such a way to maximise the production of horizontal impulse and increase horizontal velocity to the greatest possible extent (Mero and Komi, 1986; Mero et al., 1992). Mero (1988) collected force plate data for eight trained male sprinters during the first stance phase. A mean braking impulse of -3 Ns was recorded in the initial phase of stance and this was outweighed by a propulsive impulse of 90 Ns in the propulsive phase, equating to a net horizontal impulse of 87 Ns. Similarly, Salo et al. (2005) reported a net horizontal impulse of 94 Ns for a male sprinter during the first stance phase. Subsequently,

horizontal impulses (and consequently, rate of acceleration) across the second to fourth steps decreased, and this can be attributed to both an increase in braking impulse and a decrease in propulsive impulse.

Braking forces during sprinting can be minimised by either reducing the velocity of the foot at touchdown in the anterior direction (Jacobs and van Ingen Schenau, 1992; Bezodis, 2009) or decreasing touchdown distance (the distance the foot is positioned relative to the CM at touchdown; Mann and Sprague, 1980, 1983; Putnam and Kozey, 1989; Jacobs and van Ingen Schenau, 1992; Salo and Bezodis, 2004; Hunter et al., 2005). In fact, faster sprinters were found to exhibit both greater relative propulsive impulses and lower relative braking impulses during one stance in the acceleration phase (~16 m from the block), with the latter achieved by adopting a smaller touchdown distance and a more active touchdown (Hunter et al., 2004). In skeleton, the CM is likely to be more anterior to the stance foot in skeleton compared with athletic sprinting, due to the bent-over posture adopted to push the sled. Braking impulses are therefore likely to be minimal and thus, skeleton athletes should perhaps place greater emphasis on increasing propulsive impulse (through physical conditioning, for example) rather than minimising braking impulse.

Collectively, this section of the review has discussed how force capabilities can differentiate sprint start performance from a biomechanical perspective. As velocities increase across the acceleration phase, high amounts of force must be exerted across progressively shorter contact times in order to generate positive net impulse and continue accelerating. Thus, power of the lower limb extensors is clearly a crucial determinant of sprint-based performances and is likely to differentiate start ability amongst skeleton athletes. Skeleton start training should therefore be focussed towards enhancing this ability and monitoring such physical capabilities can potentially provide a valid indication of the success of skeleton training programmes.

2.7. Chapter summary

Considering the widely accepted view that a fast start phase is important in skeleton, remarkably little research has investigated the factors underlying success. The extent to which this phase has been investigated is currently limited to the characterisation of

athletes' physical profiles and some basic start performance descriptors. Previously, variation in sled velocity development between the 15 to 45 m marks has uncovered the loading phase as a potentially important (yet unexplored) section of the start. Thus, this chapter highlighted the need for a continuous measure of sled velocity across the entire skeleton start phase to better understand this variation. Due to the unexplored nature of the skeleton start, it was essential that relevant findings from similar sporting situations were identified and reviewed. Accordingly, this chapter then evaluated the research surrounding the physical and biomechanical determinants of athletic sprint starts, and identified several tests which seem to warrant inclusion in skeleton athlete monitoring protocols. However, the utility of these tests to reliably reflect skeleton athlete development is largely unknown and no research to date has attempted to identify a battery of tests which independently contribute to sprint start performance, let alone skeleton start performance. Such information is fundamental to develop an effective monitoring programme within any sport. The additional insight which can be obtained through biochemical monitoring was also presented in this chapter and longitudinal data from a truly elite training environment could contribute unique evidence towards the debate surrounding the role of testosterone in the training process. Overall, there appears to be much need and potential scope for scientific evidence surrounding the contributing factors to skeleton start performance to inform training practices.

CHAPTER 3: DESCRIPTIVE ANALYSIS OF THE SKELETON START PERFORMANCE: A COMPARISON BETWEEN DRY-LAND AND ICE TRACKS

3.1. Introduction

There is a paucity of research within the sport of skeleton and the underlying determinants of start performance are yet to be established. In consideration of this lack of knowledge, initial investigations within the skeleton start should take the form of a descriptive study. By providing an account of how the movement is typically performed, observational analyses are an important step in the research process within relatively unexplored sports techniques (Yeadon and Challis, 1994). Such an overview can provide direction for more complex future studies and thus, subsequent analyses can be better focussed on the key performance issues.

Skeleton athletes have been shown to differ from each other in several start technique descriptors on ice-tracks, specifically in the number of steps and associated time taken before loading the sled (Bullock et al., 2008). Moreover, athletes appear to adapt their performance on different tracks, perhaps to make allowances for the unique characteristics of the track (e.g. gradient and proximity of first corner) and their individual physical capabilities (Bullock et al., 2008). Although this variation is not fully understood, it could be somewhat related to the observed variance in the importance of the start across different ice-tracks (Bullock et al., 2008) and the associated track classifications (e.g. pure push tracks or pure driving tracks; Bullock et al., 2009b). For example, the track profiles of those classified as having larger driving components may provide less opportunity for faster athletes (with superior physical capabilities) to accumulate start time gains over the slower counterparts. A plausible consequence could be that, on these tracks, there is less variation in start performance across competitors and thus, driving ability is the primary determinant of race success (Bullock et al., 2009b). Further research into the differences between tracks could provide important insight regarding the determining factors of skeleton start performance on different tracks.

During the off-season, ice-tracks are closed and thus, skeleton athletes typically undergo intensified dry-land training to develop physical capacity and refine pushing skills

(Bullock et al., 2009a). The success of such training is primarily evaluated based on changes in dry-land start performance. Although somewhat assumed, the transfer of these training responses to ice-track start performance is yet to be explored and a comparison between start performances on ice-tracks and a dry-land track is warranted. Therefore, the aims of this study were to characterise skeleton start performance using selected start technique descriptors and to investigate the differences between performing push-starts on different tracks. Additionally, this study will assess the association between push-track and ice-track start performances.

3.2. Methods

3.2.1. Participants

Twelve British skeleton athletes (6 male, 6 female; mean age \pm SD = 26 \pm 4 years, height 1.74 \pm 0.06 m, mass 74.1 \pm 10.7 kg) participated in this study. This included four athletes who had achieved medals and three who had finished in the top 20, at a World Championships or Winter Olympic Games, and five athletes who had finished in the top 6 in multiple developmental level skeleton races. A Local Research Ethics Committee approved non-invasive observational investigations to be undertaken during training sessions, as was the case for this study.

3.2.2. Data collection

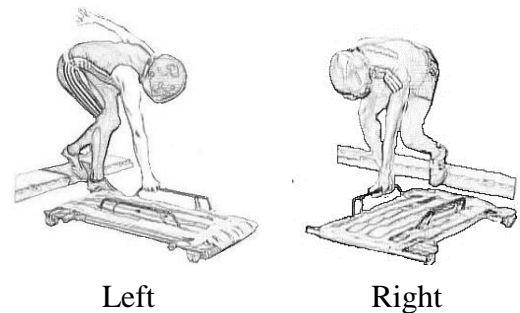
A digital video camera (Sony HC9; 50 Hz at 1/600 s shutter speed) was positioned at the 10 m mark (from the starting block), approximately 3 m away from the midline of a dry-land push-track at the University of Bath. The video camera was panned to capture the entire push-start phase (from the block to post-load). Additionally, similar video footage (50 Hz) from two National squad pre-season selection races (at Winterberg and Altenberg ice-tracks) was retrospectively obtained. Following an athlete-led warm-up, two maximal effort push-starts were performed by each athlete, on each track. The official start times (15-65 m) for each run on the ice-tracks provided a measure of overall ice-track start performance, as during competition. At the dry-land push-track, a permanent photocell system (Tag Heuer, Switzerland; 0.001s accuracy) provided a measure of start performance. However, only the time from 15-55 m was available as there are no photocells following the 55 m mark at the dry-land push-track. Nonetheless, the 15-55 m time was considered to be the closest representation of

ice-track start time and was therefore used in subsequent analyses. Photocell timing data were not available for the second run at Winterberg and thus, a total of 60 runs (five for each athlete across three tracks) were analysed in this study.

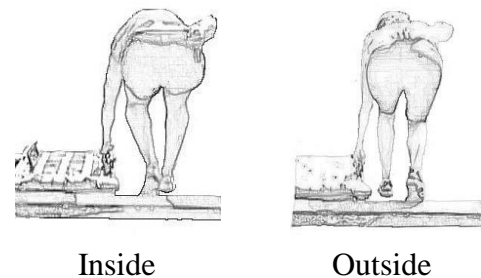
3.2.3. Data analysis

Average start velocity was calculated for each push-start by dividing start time by the distance across which this time relates to (50 m for ice-tracks and 40 m for dry-land push-track). Each recording was analysed for a number of technique descriptors, which were defined as follows:

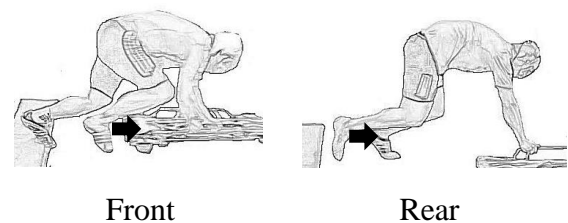
Starting side The side of the sled an athlete pushed from when facing down the track



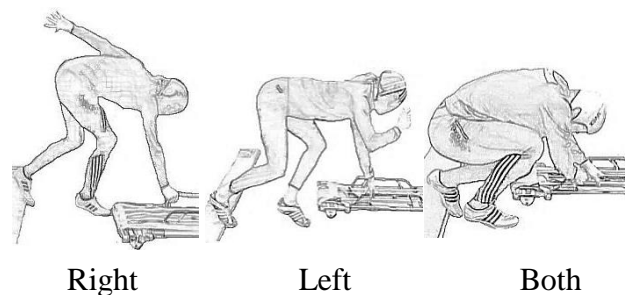
Rear leg The rearmost leg during block set-up



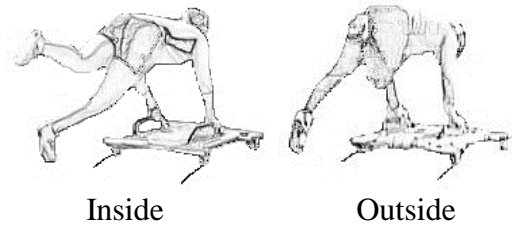
First foot off The first foot to lose contact with the ground



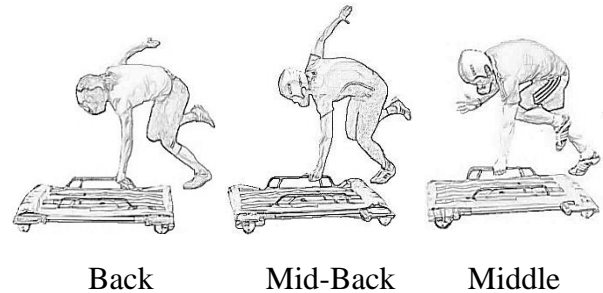
Pushing arm(s) The arm(s) that an athlete pushes the sled with off the block



Loading leg The leg used to take the final step before loading the sled



Hand position The hand position used to push the sled



Number of arm swings The number of arm swings taken before loading the sled (one forward swing and one backward swing = 2 arm swings)

Total number of steps The total number of ground contact phases before loading the sled

In addition to the above variables, average step frequency was calculated across each push-start phase. This was analysed across an even number of steps (complete strides) to avoid any potential effect of asymmetry. As the first step from the blocks is markedly longer in duration and the initiation of movement is difficult to identify accurately, this step was disregarded from the analysis, in line with a previous study in athletic sprinting (Salo et al., 2011). Thus, the times (0.02 s accuracy) of the first and final stance toe-off were recorded and the time difference between these events was calculated.

Equation 3.1 was then used to calculate average step frequency (SF), where the number of steps (n_s ; always an even number) was divided by the time difference between the instances of the first (t_i) and final (t_f) stance toe-off:

$$SF = \frac{n_s}{t_f - t_i} \quad [3.1]$$

3.2.4. Statistical analysis

Means and standard deviations were calculated for the number of steps, time between first and final stance toe-off, average step frequency and average start velocity for each athlete, at each track. A group average and standard deviation for each track was then calculated for each of these variables. To assess the magnitude of the differences between the number of steps, time between first and final stance toe-off, and average step frequency across tracks, effect sizes were calculated (Cohen, 1988). Pearson r correlation coefficients were then used to explore the relationships between dry-land start performance (15-55 m average start velocity) and ice-track start performance (15-65 m average start velocity; at both Winterberg and Altenberg). Additionally, for each of the three tracks, athletes start performance levels were ranked between 1 and 12, based on average start velocity (the fastest athlete was assigned a ranking of one). Spearman's ρ correlations were then used to assess the association between start performance rankings on the three tracks. The relationships between average step frequency and average start velocity, and between average step frequency and the number of steps taken, were also evaluated at each track using Pearson r correlations.

For all effect sizes and correlation coefficients, 90% confidence intervals (CI) were calculated and magnitude-based inferences derived as previously suggested (Batterham and Hopkins, 2006). Effects sizes were interpreted on the following scale: < 0.2 , trivial; 0.2 to 0.6, small; 0.6 to 1.2, large; and > 2.0 , very large, as previously suggested (Hopkins et al., 2009). Thus, a threshold for a practically important effect was set at 0.2, with the values between -0.2 and +0.2 signifying a trivial effect. As 90% CI provide a range within which the true effect statistic is likely to fall, effects were considered to be substantially positive only if the effect statistic was greater than +0.2 and the lower confidence limit did not cross -0.2. Conversely, if the effect statistic was less than -0.2 and the upper confidence limit did not extend past +0.2, the effect was deemed substantially negative. An effect was considered unclear if the 90% CI crossed over both +0.2 and -0.2. Similarly, the magnitude of the correlation coefficients were interpreted on the following scale: < 0.1 , trivial; 0.1 to 0.3, small; 0.3 to 0.5, large; and > 0.7 , very large (Cohen, 1988). A threshold of 0.1 was therefore set for the smallest practically important effect, through which clear (both positive and negative) and unclear relationships were defined using CI, following the same methods as above. The p values associated with these differences and relationships will not be presented in the

results section of this chapter. However, statistical significance can be assumed if zero does not fall within the CI because the possibility of a zero effect (equivalent to a null hypothesis) can be rejected.

3.3. Results

3.3.1. Between-athlete variation in start technique descriptors

Athletes adopted a consistent block set-up across the different tracks, however there was marked between-athlete variation in all block set-up variables (Table 3.1). Seven athletes initiated the push-start from the left hand side of the sled, whereas five athletes pushed from the right hand side. The inside leg (closest to the sled) was rearmost on the block for eight athletes, whereas four athletes placed their outside leg on the block. However, there did not seem to be a trend between starting side and rear leg on the block. Typically, the rear leg was the first to leave the ground, except in the case of athlete A5 who took the first step with the front foot. Four athletes used a double handed push-off during the first step from the block, however, after the initial push-off from the block and the first step, all athletes used the inside arm only to push the sled.

Table 3.1. Start technique descriptors for each athlete from the block.

Athlete	Starting side	Rear leg	First foot off	Pushing arm(s)	Hand position
A1	L	I	B	R	Back
A2	R	O	B	L	Back
A3	L	O	B	R	Mid-Back
A4	R	I	B	L	Back
A5	R	I	F	D	Middle
A6	R	I	B	D	Back
A7	L	I	B	R	Middle
A8	L	I	B	D	Back
A9	L	O	B	R	Middle
A10	R	O	B	L	Back
A11	L	I	B	R	Back
A12	L	I	B	D	Back

L = left, R= right, D= both (double handed push-off), I = inside, O = outside, B = Rear leg, F = front leg.

There was also between-athlete variation in the hand position on the sled but, once again, this was consistent within-athletes and across tracks. Athletes typically used the outside leg (furthest away from the sled) during the final ground contact before loading onto the sled. However, this was not always the case, as one athlete (A8) loaded with the inside leg at Winterberg only. Athletes generally co-ordinated one arm swing with one step but the total number of arm swings was dependent on the block starting position and first foot off from the block.

The average number of steps taken, the time between the first and final stance toe-off and the average step frequency for each athlete are provided in Table 3.2, alongside the group mean for each track. There was marked variation in the number of steps taken before loading at each track. For example, the number of steps ranged from 14 to 19 steps at the dry-land push-track, 15 to 21 steps at Altenberg and 12 to 19 steps at Winterberg. Similarly, the time between the first and final stance toe-off also varied considerably (2.79 to 3.82 s at the dry-land push-track, 3.09 to 4.47 s at Altenberg, 2.30 to 3.68 s at Winterberg). As a consequence, a wide range of average step frequencies were also observed at each track (4.06 to 4.85 Hz at the dry-land push-track, 4.10 to 4.84 Hz at Altenberg and 4.17 to 4.89 Hz at Winterberg).

3.3.2. Between-track variation in start technique descriptors

As shown in Table 3.2, athletes took a substantially higher number of steps at the dry-land push-track (16 ± 1 steps; effect size $\pm 90\%$ CI = 0.72 ± 0.43) and Altenberg (18 ± 2 steps; effect size = 1.85 ± 0.43) than at Winterberg (15 ± 2 steps). Additionally, the total number of steps taken before loading was found to be substantially higher at Altenberg compared with that at the dry-land push-track (effect size $\pm 90\%$ CI = 1.51 ± 0.35). The time that athletes spent pushing the sled (between first and final stance toe-off) was consequently shown to be substantially longer at the dry-land push-track (3.37 ± 0.29 s; effect size $\pm 90\%$ CI = 0.85 ± 0.55) and Altenberg (3.89 ± 0.39 s; effect size = 2.03 ± 0.38) compared with Winterberg (3.06 ± 0.42 s). Additionally, athletes spent a substantially longer period of time pushing at Altenberg compared with the dry-land push-track (effect size $\pm 90\%$ CI = 1.53 ± 0.28). However, average step frequency was found to be substantially higher at Winterberg (4.37 ± 0.20 Hz) compared with the dry-land push-track (4.30 ± 0.22 Hz; effect size $\pm 90\%$ CI = 0.34 ± 0.21) and Altenberg (4.32 ± 0.21 Hz; effect size = 0.26 ± 0.19).

Table 3.2. The average number of steps taken before loading, time between first and final stance toe-off, and average step frequency for each skeleton athlete and the group mean (\pm SD) at three tracks.

Athlete	Dry-land push-track			Winterberg ice-track			Altenberg ice-track		
	Total number of steps	Time first – final stance TO (s)	Average step frequency (Hz)	Total number of steps	Time first – final stance TO (s)	Average step frequency (Hz)	Total number of steps	Time first – final stance TO (s)	Average step frequency (Hz)
A1	16	3.15	4.44	16	3.18	4.40	19	3.90	4.36
A2	15	3.44	4.07	15	3.32	4.22	20	4.47	4.25
A3	18	3.82	4.45	17	3.50	4.57	21	4.39	4.56
A4	16	3.34	4.19	14	2.72	4.41	19	3.94	4.31
A5	19	3.71	4.85	19	3.68	4.89	21	4.13	4.84
A6	15	3.32	4.22	14	2.76	4.35	18	3.88	4.13
A7	14	2.79	4.30	12	2.30	4.35	15	3.09	4.21
A8	15	3.01	4.32	15	3.24	4.32	18	3.74	4.28
A9	15	3.67	4.36	13	2.78	4.32	19	4.15	4.34
A10	15	3.36	4.17	13	3.36	4.17	15	3.38	4.14
A11	16	3.34	4.19	14	2.80	4.29	18	3.70	4.32
A12	16	3.45	4.06	16	3.36	4.17	18	3.90	4.10
Group	16 \pm 1[^]	3.37 \pm 0.29[^]	4.30 \pm 0.22	15 \pm 2	3.06 \pm 0.42	4.37 \pm 0.20^{^#}	18 \pm 2^{^*}	3.89 \pm 0.39^{^*}	4.32 \pm 0.21

N.B. Average step frequency calculated across the steps from the first to final stance toe-off (TO). * denotes substantially higher than at the dry-land push-track. ^ denotes substantially higher than at Winterberg. # denotes substantially higher than at Altenberg.

3.3.3. Relationship between step frequency and performance on different tracks

Positive relationships were observed between the number of steps taken and average step frequency at Altenberg ($r = 0.70$, 90% CI = 0.31 to 0.89), Winterberg ($r = 0.69$, 0.29 to 0.88) and the dry-land push-track ($r = 0.73$, 0.36 to 0.90), as shown in Figure 3.1. Additionally, clear positive relationships were observed between average step frequency and average start velocity at Altenberg ($r = 0.52$, 90% CI = 0.03 to 0.81), Winterberg ($r = 0.67$, 0.26 to 0.88) and the dry-land push-track ($r = 0.61$, 0.16 to 0.85).

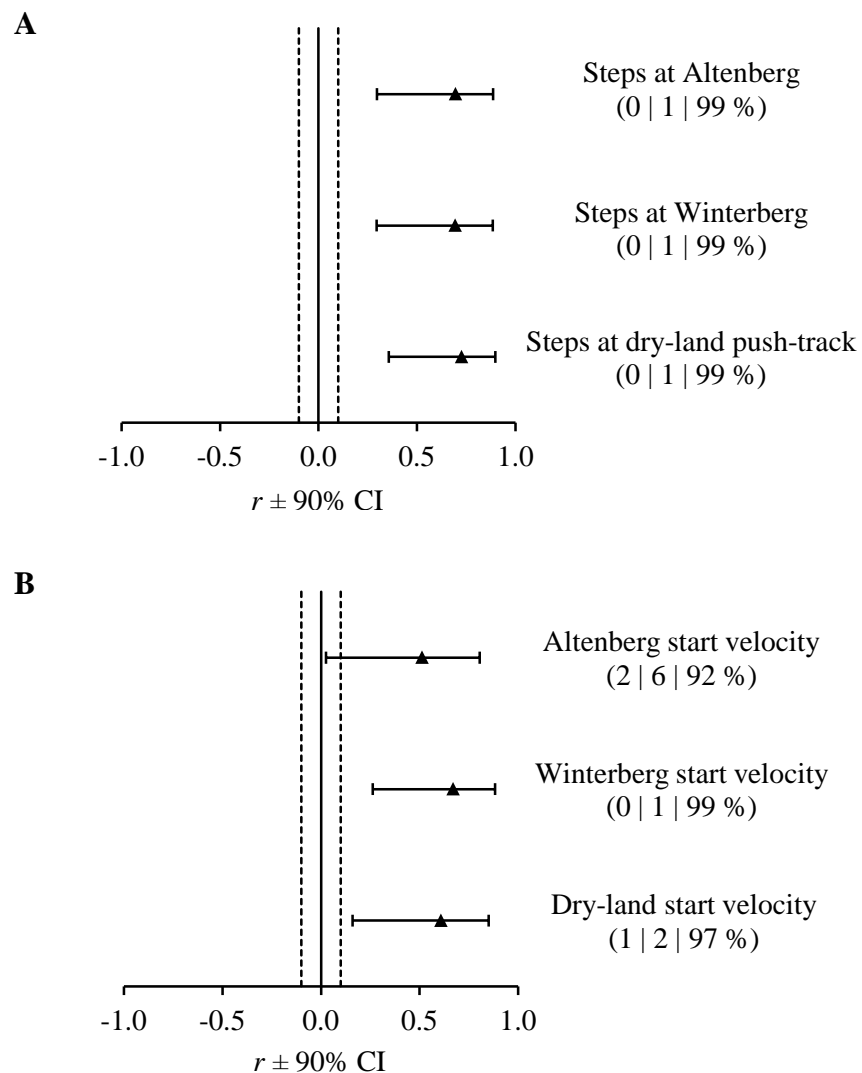


Figure 3.1. Correlation coefficients (r) and 90% CI for the relationships between average step frequency and total number of steps (A) and between average step frequency and average start velocity (B) for 12 athletes on three different tracks. Central area ($r = 0.0 \pm 0.1$) indicates a trivial relationship. Percentages in brackets represent the likelihoods that the relationship is negative | trivial | positive.

3.3.4. Relationship between dry-land push-track and ice-track start performance

Clear positive relationships were observed between average start velocities at the dry-land push-track and at both ice-tracks, Winterberg ($r = 0.96$, 90% CI = 0.88 to 0.99) and Altenberg ($r = 0.82$, 0.54 to 0.94). The start performance ranking of each athlete on the three different tracks is illustrated in Figure 3.2.

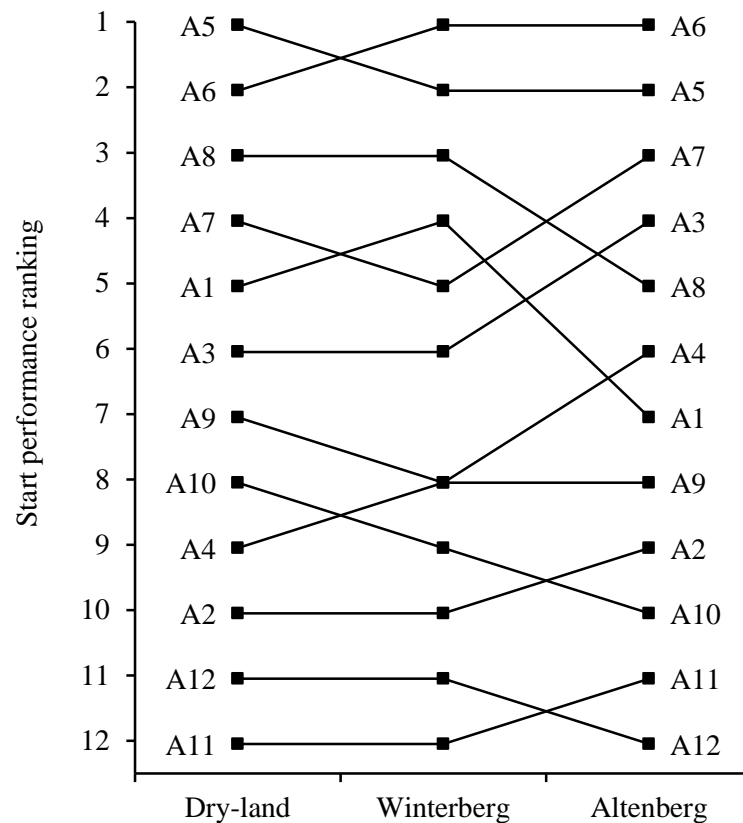


Figure 3.2. The start performance rankings (based on average start velocity) achieved by 12 athletes on each of the three tracks. Ranking 1 denotes the athlete with the fastest start velocity at each track.

Five athletes achieved the same start performance ranking on the dry-land push-track and the Winterberg ice-track (Spearman's $\rho = 0.97$, 90% CI = 0.91 to 0.99) and three athletes were ranked the same based on the average start velocity achieved at the Winterberg and Altenberg tracks ($\rho = 0.90$, 0.73 to 0.97). A clear Spearman's rank correlation was observed between the start performance rankings at the dry-land push-track and the Altenberg track ($\rho = 0.70$, 90% CI = 0.31 to 0.89), however, no athlete was ranked the same at these tracks.

3.4. Discussion

The primary purpose of this study was to characterise how different skeleton athletes perform the start using selected technique descriptors and how these vary across tracks. The main findings were that athletes vary considerably in the way that they perform the start phase, with marked variation in all performance descriptors. However, skeleton athletes also make adjustments to the number of steps they take before loading across different tracks, which seem to coincide with unique track profiles and the associated physical requirements.

There was marked variation in the block set-up adopted by different athletes amongst the group (Table 3.1) perhaps reflecting the universal lack of knowledge concerning superior start technique and/or individual preference (which may perhaps be related to physical and anthropometric characteristics). Importantly, however, block set-up was found to be consistent across the dry-land push-track and ice-tracks. Thus, during dry-land training, athletes appear to replicate how they perform the block phase in competition, in terms of the particular technique descriptors used in this study. There did not seem to be many clear trends between start performance level and the specific technique descriptors outlined in Table 3.1. However, it may be noteworthy that the fastest starters at the push-track (A5, A6 and A8) were three of the four athletes who initiated the push using two hands. On the other hand, as these three athletes are all male, it is problematic to make solid inferences about the influence of these different starting styles based solely on these observations. In fact, the only female athlete who adopted a double handed push-off was ranked in eleventh place on the dry-land push-track and at Winterberg, and twelfth at Altenberg. Although these four athletes initiated the push from the block using both hands, following the first stance toe-off, all athletes pushed with one hand only. Previously, Bullock et al. (2008) reported that a large portion of skeleton athletes (40-60%) in elite female races (three World Cup races in the 2005-2006 season) used a two-handed push for the entire start phase (from the block to load phase). Additionally, Bullock et al. (2008) noted that the fastest starters in each race were those who adopted one-handed pushes, whereas two-handed pushes were dominant amongst the slower starters. Collectively, this may provide some evidence for the evolution of the skeleton start across recent years towards single-handed push-starts (following the initial push-off from the block).

In addition to the variation in block set-up, between-athlete differences in the amount of time spent pushing the sled before loading was observed on each track. This includes variation in both the number of steps and the time between first and final stance toe-off (Table 3.2), which could be somewhat determined by physical capabilities. Athletes who took a greater number of steps before loading also exhibited the higher average step frequencies for each of the three tracks (Figure 3.1). For example, the athlete with the greatest number of steps before loading (A5) at the dry-land push-track, Winterberg and Altenberg was also found to exhibit the highest average step frequencies (19, 19 and 21 steps and 4.85, 4.89 and 4.84 Hz, respectively). Relative to previous published data, it is clear that athlete A5 is able to attain high step frequency. For example, average step frequencies across athletics 100 m races have been shown to range from 4.47 to 5.05 Hz in the World's fastest 100 m sprinters (Salo et al., 2011). Conversely for athlete A7, who took considerably fewer steps than A5 at the dry-land push-track, Winterberg and Altenberg (14, 12 and 15 steps, respectively), lower step frequencies were exhibited (4.30, 4.35 and 4.21 Hz, respectively).

A positive relationship was observed between the number of steps taken before loading and the average step frequency recorded at each of the tracks (Figure 3.1). A greater number of stance phases will increase the amount of time across which net positive impulse (in the direction parallel to the track) can be generated, and thus, provides more scope for the athlete to accelerate themselves and the sled. If an athlete can continue to produce positive net impulse across these additional steps, a further increase in velocity will occur which is likely to be associated with the attainment of higher step frequency (Luhtanen and Komi, 1978; Kivi et al., 2002). Indeed, average step frequency was also found to be positively related to average start velocity at all three tracks in the current study (Figure 3.1).

In skeleton, the optimum time at which to load the sled is theoretically when acceleration through ground contact is no longer possible. If an athlete has not loaded by the instance of maximum running velocity attainment, the post-load increase in velocity (due to the gravity component) will be reduced. This is likely to be detrimental to overall start performance and perhaps the subsequent driving phase. Therefore, in theory, taking a greater number of steps would only be beneficial if the rate of acceleration through ground contact is greater than that due to the component of gravity.

However, the positive effect on start performance is not guaranteed because the subsequent influence of increasing the number of steps (and velocity) on the effectiveness of the loading phase is yet to be investigated (this will be addressed in Chapter 7). It is conceivable that a skeleton athlete's physical prowess may, therefore, regulate the velocity and distance (or number of steps) at which they load the sled. As velocity increases, the time available to generate positive net impulse (i.e. stance time) is reduced during sprinting (Luhtanen and Komi, 1978; Kivi et al., 2002). Physically developed athletes, who can generate large relative forces across progressively shorter ground contacts, may be able to continue accelerating (at a rate greater than that due to the gravity component) further down the track and achieve higher start velocities. Conversely, acceleration may be more limited for athletes who are less able to exert large relative forces rapidly. Thus, less developed skeleton athletes may attain maximum velocity and load the sled at an earlier position on the track. Currently, this is somewhat speculative and the relationships between physical capabilities and skeleton start performance will be further explored in later sections (Chapters 4 and 7).

Athletes appear to modify certain start technique descriptors depending on the track, with differences observed between the number of steps, time between the first and final stance toe-off, and the associated average step frequency. Although step frequency data have not been reported in the skeleton start research previously, elite female athletes have previously been shown to take a varying number of steps and time to load across three international races (Bullock et al., 2008). These differences have been attributed to the unique characteristics of individual tracks, including the gradient of the start and proximity of the first corner, which are perceived by international coaches to determine the importance of the start to overall finish time (Bullock et al., 2009b). In the current study, athletes took a greater number of steps and a longer time to load at Altenberg than at the dry-land push-track (Table 3.2). Athletes also took fewer steps and a shorter time to load at Winterberg compared with both the dry-land push-track and Altenberg (Table 3.2). Although the exact start track profiles are not available, it is well acknowledged that the start phase at Winterberg has a markedly steeper gradient compared with at Altenberg. Furthermore, average step frequency was also found to be higher at Winterberg than at both the dry-land push-track and Altenberg. A potential explanation for these differences could be that on steeper tracks like Winterberg, the athlete and sled will be subject to a greater level of acceleration due to a larger gravity

component. Thus, on steeper tracks, it is feasible that skeleton athletes will accelerate faster and attain higher velocities than on flatter tracks, and consequently higher step frequencies are to be expected (Kivi et al., 2002). A continuous measure of sled velocity is required to further investigate the differences between start performances on tracks with varying profiles (this will be addressed in Chapter 7).

As previously described, clear positive relationships between average step frequency and average start velocity were observed on all three tracks and thus, attaining high step frequency appears to be important to achieve a fast start in skeleton. A greater portion of the variance in start performance could be explained by step frequency at Winterberg (46%), followed by the dry-land push-track (35%) and finally Altenberg (27%). Thus, it appears to be even more important to attain high average step frequency at Winterberg, compared with the other two tracks. The aforementioned variation in the track gradient and total number of steps taken (with steeper gradient and fewer steps taken at Winterberg) could be somewhat related to the relative importance of attaining high step frequency. For instance, it seems as though there are more opportunities for skeleton athletes to attain higher velocities and step frequencies on the steeper Winterberg track (which has been previously categorised as a 'pure push track'; Bullock et al., 2009b) compared with the longer, flatter profile at Altenberg (considered to be a 'pure driving track'). As such, step frequency appears to differentiate the start abilities of skeleton athletes to a greater extent on the steeper tracks, whereas step frequency seems to contribute less to overall start performance on the flatter profiles. It is plausible that the driving phase would consequently have a greater influence on overall race outcome at Altenberg, as previously suggested (Bullock et al., 2009b).

Average start velocity at the dry-land push-track was found to be positively related to the average start velocity at both Altenberg and Winterberg. Thus, it appears that starts on the dry-land push-track do, to an extent, reflect ice performances. However, when athletes' start performances on each track were ranked, some discrepancies between performance levels were revealed. For example, five athletes were found to rank the same at both the dry-land push-track and Winterberg tracks, however, no athlete was ranked the same at the dry-land push-track and Altenberg. Thus, although clearly there are similarities between the performances, different athletes do appear to favour different tracks. This could potentially reflect both the individual strengths of the

athletes and the unique requirements of the different tracks. Although differences in start velocity between the first and twelfth ranking ranged from 0.9 and 1.2 m·s⁻¹ across the three tracks in this study, the margins between adjacent rankings were sometimes less than 0.1 m·s⁻¹ (or 0.05 s). These seemingly small differences can often prove to be practically very significant in skeleton, with some race outcomes decided by only 0.01 s (FIBT, 2015a). Thus, the differences in start performance rankings across tracks may, in fact, be significant.

Importantly, the dry-land push-track appears to better replicate the start phase at Winterberg (which is considered to be a ‘pure push track’) than at Altenberg (where success appears to be more dependent on driving ability). For example, dry-land performances were more closely matched, in terms of average start velocities and performance based rankings, with those at Winterberg ($r = 0.96$ and $\rho = 0.97$, respectively) compared with Altenberg ($r = 0.82$ and $\rho = 0.90$, respectively). Thus, the dry-land push-track provides a facility in which to train and practise skeleton starts in a manner that seems to be more reflective of performance on tracks where the start phase is considered to be more crucial to overall success.

3.4.1. Conclusion

Skeleton athletes appear to adopt individual strategies during the start phase, perhaps reflecting differences in physical capabilities and the overall lack of knowledge surrounding superior performances. Importantly, consistency was observed across tracks in terms of block set-up and general pushing technique (pushing arm and loading leg). However, the number of steps taken, time between first and final stance toe-off, and average step frequencies seem to be track dependent. These differences appear to coincide with the unique characteristics of the track and the associated track classifications which have previously been defined (Bullock et al., 2009b). For example, fewer steps were reported at the steeper Winterberg track (upon which a faster start is considered to be more important for success) than on the flatter profile at Altenberg. Additionally, step frequency was identified as a contributing factor to start performance, particularly on the steeper, ‘pure push’ track of Winterberg. Finally, although dry-land push-track start performances are certainly comparable to those on ice-tracks, some differences do exist and may warrant consideration when preparing for competitions on tracks with varying profiles.

CHAPTER 4: DEVELOPING AN UNDERSTANDING OF THE KEY PHYSICAL CHARACTERISTICS UNDERLYING SKELETON START PERFORMANCE

4.1. Introduction

Chapter 3 revealed marked between-athlete variation in a number of start technique descriptors, which may be partly attributable to the differing physical capabilities amongst athletes. Sport scientists and coaches often endeavour to establish the key physical determinants of elite sports performances with the view to optimising training strategies and maximising chances of success in competition. Previous descriptive studies have attempted to identify some key performance indicators in skeleton (Sands et al., 2005), as well as bobsleigh (Osbeck et al., 1996) and luge (Crossland et al., 2011). However, the relationships between these physical characteristics and their independent contributions to skeleton start performance are not fully understood and thus, current testing batteries and training strategies are based on limited scientific evidence.

In previous studies, measures of lower limb power have been found to strongly correlate with push-start performance in both US national skeleton (Sands et al., 2005) and bobsleigh (Osbeck et al., 1996) teams. Specifically, vertical jump and sprint performance measures were reported to be the most valuable predictive tools for identifying superior starters in both sports (Osbeck et al., 1996; Sands et al., 2005). Thus, these types of physical tests are typically incorporated into athlete monitoring programmes, and a successful skeleton talent identification and development model centred around these tests has previously been documented (Bullock et al., 2009a). However, there is likely to be a crossover between these physical tests in terms of the aspect of physical ability they are measuring. To the author's knowledge, no attempts have been made in the scientific literature to uncover a set of independent predictors of skeleton start performance. Such information is crucial in order for sports scientists and coaches to effectively and efficiently quantify an athlete's development.

At the time of the Sands et al. (2005) publication, the sport of skeleton was a relatively new addition to the Winter Olympic programme. As acknowledged by the author, the US national skeleton athletes at that moment were not well accustomed to high intensity

resistance training. This is perhaps reflected in the somatotypes reported, with some athletes exhibiting endomorphic profiles (Sands et al., 2005). However, as the sport has matured and intensified periods of training have been shown to accelerate talent development and yield success in skeleton (Bullock et al., 2009a), extensive training programmes have become the norm. The findings of Sands and colleagues (2005) may therefore no longer be applicable to the current well-trained skeleton athletes. Thus, the primary aims of this study were to characterise the physical attributes of a group of current skeleton athletes and establish the key physical characteristics underlying start performance.

4.2. Methods

4.2.1. Participants

Fourteen British skeleton athletes (three male and four female elite squad athletes; six male and one female talent squad athlete) participated in this study. Elite squad skeleton athletes included six athletes who had competed in multiple World Cup races and/or at the World Championships (two athletes medalled in at least one race) and one athlete who had medalled in multiple races at the European Cup level (development level competition). Talent squad skeleton athletes were identified in 2011/12 through a national talent search programme and were preparing for their first competitive season (2013) on the developmental level circuit, with ambitions to compete in the 2018 Winter Olympics. The mean age, height and mass of the athletes recorded at the start of the testing period are presented in Table 4.1. A University of Bath Research Ethics Approval Committee for Health provided ethical approval for the physical testing to be conducted. A NHS Local Research Ethics Committee provided ethical approval for athletes to undergo dual-energy X-ray absorptiometry (DXA) scans. All athletes provided written consent prior to the collection of any data.

Table 4.1. Descriptive characteristics for 14 skeleton athletes (mean \pm SD).

	Height (m)	Mass (kg)	Age (years)
Male elite squad (n = 3)	1.79 \pm 0.10	84.0 \pm 6.9	26 \pm 2
Female elite squad (n = 4)	1.71 \pm 0.02	68.3 \pm 3.0	24 \pm 2
Male talent squad (n = 6)	1.74 \pm 0.04	76.3 \pm 7.2	23 \pm 1
Female talent squad (n = 1)	1.58	56.3	21

4.2.2. Data collection and processing

Data were collected across a series of nine (talent) or eleven (elite) 2-day testing sessions across two summer training seasons (March-September 2012 and April-October 2013). A schematic outlining the primary emphases of training blocks across the two training seasons within which data were collected is provided in Figure 4.1, alongside the timings of testing sessions.

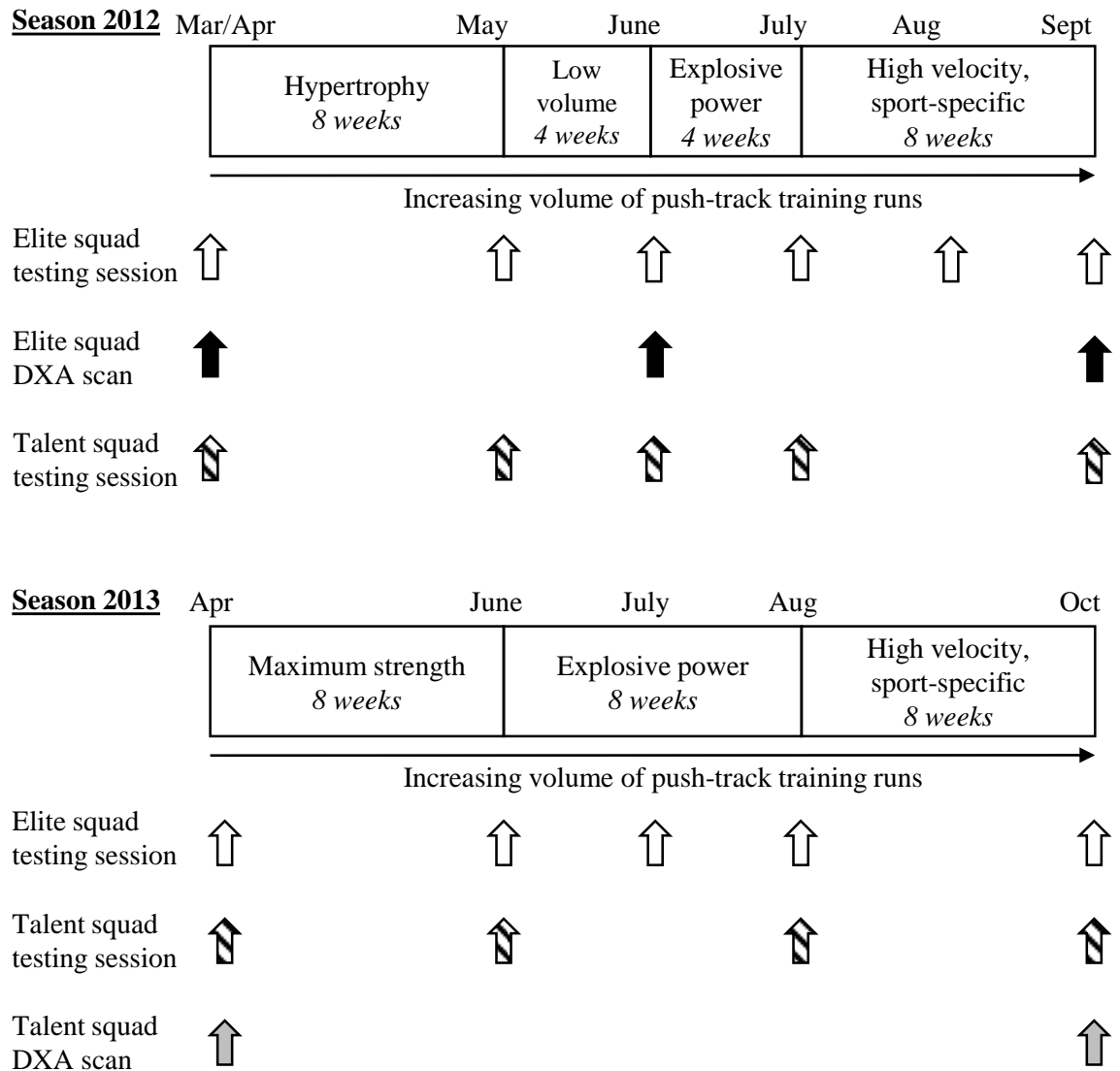


Figure 4.1. A schematic of the programmed training and scheduled testing across two training seasons.

Each athlete was scheduled to complete five physical tests over each testing period (full testing schedules for the elite and talent squad are provided in Table 4.2 and Table 4.3, respectively). This included flexibility, push-track and sprint testing on the first testing

day and countermovement jump and leg press testing on the second day. Blood analyses were also conducted alongside these tests and will be discussed in Chapter 5. This schedule was consistent across all sessions and athletes were asked to refrain from vigorous exercise in the 36 hours before testing.

Table 4.2. A typical testing schedule for an elite squad athlete.

Testing day 1		Testing day 2	
1000	Baseline blood sample (pre push-track)	0900	Baseline blood sample
1030	Flexibility tests	1130	Blood sample (pre jump tests)
1145	Push-track tests	1145	Countermovement jump tests
1215	Blood sample (post push-track)	1215	Blood sample (post jump tests)
1345	Sprint tests	1400	Keiser leg press tests

Table 4.3. A typical testing schedule for a talent squad athlete.

Testing day 1		Testing day 2	
1030	Baseline blood sample (pre push-track)	0800	Baseline blood sample (pre jump tests)
1045	Flexibility tests	0830	Countermovement jump tests
1145	Push-track tests	0900	Blood sample (post jump tests)
1215	Blood sample (post push-track)	1000	Keiser leg press testing
1345	Sprint tests		

Body composition was estimated by analysing DXA scans at three time points (at the beginning of the first training season, following the first eight-week heavy resistance training block and at the end of the first training season) for the elite squad (Figure 4.1). For the talent squad, body composition was estimated for five athletes (four male and one female) at only two time points (beginning and end of the second training season; Figure 4.1) due to technical difficulties with the scanner at the mid-season time point.

Twelve out of fourteen athletes participated in the testing sessions across both seasons. Two talent squad athletes participated in the testing sessions across one training season only (one in 2012 and one in 2013). Some athletes were unable to complete all tests at every time point due to injury, illness or technical difficulties with the equipment. In the first training season, 59 complete data sets (from a possible 72) were obtained and 40 complete data sets (from a possible 59) were collected in the second training season.

Flexibility testing

Athletes firstly completed an eight-minute incremental cycle warm-up. A trained physiotherapist then conducted three flexibility tests to assess hamstring length: two knee extension assessments (KEA) with hip at 90° and 110° to the horizontal, in addition to a sit and reach (SR) test. Two KEA test scores for each leg (at each angle) and three SR scores were recorded. Talent squad athletes completed only the SR tests at each testing session due to the limited availability of the physiotherapist. The KEA tests were conducted from a supine position with the contralateral leg fixed to a bench by a strap. The hip joint was flexed to the respective angle (90 or 110° from horizontal) and the athlete's knee was then passively extended upwards until a strong hamstring stretch was felt. The knee angle was then recorded using a manual goniometer (Figure 4.2). Previously, high intra-tester reliability has been found for similar knee flexion/extension measurements using manual goniometers (Rothstein et al., 1983) and typical errors of less than 1° have been reported (dos Santos et al., 2012).



Figure 4.2. Knee extension angle flexibility test (90° hip angle).

For the SR tests, athletes were required to maintain full knee extension and flat foot contact with the sit and reach box (Body Care, Warwickshire, UK) as they reached forward and held the maximum stretch for at least two seconds. The distance that a subject could reach and hold for this period was measured to the nearest centimetre.

Push-track testing

Athletes completed and documented an individual 30-minute competition warm-up at the first data collection session which was replicated at subsequent testing sessions. Push-track testing consisted of six maximum effort push-starts on an outdoor dry-land push-track at the University of Bath. The push-track simulated the typical topography of an ice-start track, beginning with a slight decline (~2% gradient) until the brow (~19 m from the starting block), where the gradient rapidly increases (~12% gradient). Three push-starts were initiated from the standard block position of the track and three when the block was moved 2.5 m backward (in order to create a longer, flatter start profile). Each push-start was performed from the participant's preferred starting side, with a recovery period of at least three minutes between efforts. Split times were recorded at various points by a permanent photocell system (Tag Heuer, Switzerland; 0.001s resolution) along the track (at 10, 15, 38, 45 and 55 m from the standard block position; Figure 4.3). However, the time from 15-55 m (closest representation available of the ice-track 'start time') could not be used as a performance measure because different parts of the sled or athlete were found to trigger the 15 m mark photocell in the first season. Instead, the 38 and 45 m split times were used to calculate average velocity (V_{38-45}) over this distance. Pilot testing revealed this split to be a robust measure of average velocity as all athletes had loaded the sled by the 38 m mark and therefore photocells were consistently triggered by the helmet (and not by other body parts, as during the initial stages of the start in the first season).

Additionally temporary photocells (Brower Timing System; Utah, USA; 0.001s accuracy) were placed at 14.5 and 15.5 m from the starting block (Figure 4.3). These photocells were consistently triggered by the front of the sled and so allowed average velocity to be calculated across this section, providing sled velocity at the 15 m mark (V_{15}). This is a more relevant performance measure than time to 15 m mark as unlike sprinting (where an external trigger initiates the clock) competition timing does not begin until the athlete reaches the 15 m mark. Therefore, to increase V_{15} , skeleton athletes could theoretically increase net impulse through taking longer ground contact times and consequently increase the time spent in the first 15 m without negatively impacting their overall descent time. Indeed, variation amongst the velocity-time profiles has previously been exhibited by less-than-perfect correlations ($r = -0.73$

and -0.71, for St. Moritz and Sigulda, respectively) between time to 15 m and V_{15} in three women's World Cup races (Bullock et al., 2008).

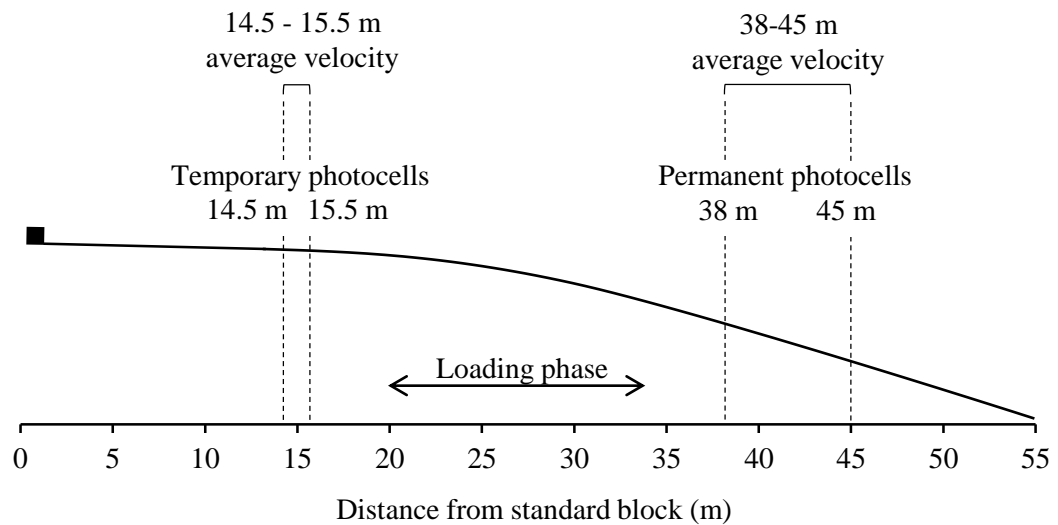


Figure 4.3. Schematic representation of the push-track set-up and start performance outcome measures.

Sprint testing

Athletes completed and documented an abbreviated warm-up (due to a short break after the push-track tests) during the first testing session which was replicated before subsequent sprint testing sessions. Athletes performed three maximal 30 m unresisted sprints and three maximal 30 m resisted sprints on an indoor synthetic running track. At least a three minute recovery period was taken between the runs. Sprints started from a three-point position which simulated the athletes' preferred block set-up during a push-start (using the same front and rear legs, and allowing the same arm to swing freely forward). The resistance was provided by a weighted sled (10 kg and 7.5 kg for male and female athletes, respectively), which was connected by a waist-harness and towed behind. Photocells (Brower Timing System; Utah, USA; 0.001s resolution) were placed on tripods at the 10, 15 and 30 m marks. These were set-up at waist height to reduce errors caused by inconsistent body configurations (Yeadon et al., 1999). Timing was initiated when the athlete released their hand from a touch pad placed on the starting line and split times were recorded by each set of photocells. Moir et al. (2004) previously reported good reliability ($CV < 2\%$) for sprint performance measures (time to 10 m and 20 m) collected in a similar manner to that of the current study.

Countermovement jump testing

On the morning of the second testing day, athletes performed an eight-minute incremental cycle warm-up and three warm-up countermovement jumps (CMJs) prior to jump testing. Vertical jump performance was assessed across a series of loads: unloaded (hands remained on hips throughout jump), 5 kg (weight plate held across the chest), barbell (15 kg or 20 kg barbell held across the back of the shoulders for females and males, respectively) and 50% body mass (loaded barbell to the nearest 0.25 kg, held across the back of the shoulders). Three jumps were performed at each of these loads with at least a two minute recovery period between efforts. Longer recovery periods (3 - 4 minutes) were given between the 50% body mass jumps. Each of these jumps was performed in a squat rack and on a force plate (Fi-tech; Skye, Australia) which sampled vertical ground reaction force data at 600 Hz. The vertical force (Fz) data were filtered using a low-pass second-order recursive Butterworth filter. Residual analyses of 48 representative jumps revealed optimum cut-off frequencies ranging from 67 to 98 Hz. A mean value of 82 Hz was calculated and this cut-off frequency was used in all subsequent analyses. Several variables including maximum centre of mass displacement (CM_{disp}), peak force, peak power, mean power and average rate of force development were calculated from the filtered Fz data. The assessment of vertical jump ability through force plate analysis has previously been shown to have excellent reliability and is often used as a criterion against which alternative methods are validated (Aragón-Vargas, 2000).

Take-off was defined as the first time point where Fz fell below 5 N. There was some evidence of ‘ringing’ in the force data following take-off and thus, in order to avoid introducing calculation errors when integrating Fz during the flight phase, the maximum CM_{disp} calculations were modified as follows:

Vertical velocity (v) was calculated using the impulse-momentum relationship:

$$v = \frac{\int_{t_0}^{t_n} F_{Z_{net}} (dt)}{m} \quad [4.1]$$

Where $F_{Z_{net}}$ denotes vertical force above body weight (plus any additional load), m is the mass of the subject (plus the mass of any additional load) and t_0 and t_n are the first and n^{th} time point, respectively.

Equation 4.1 was integrated to obtain CM_{disp} (m) at any time point during the jump:

$$CM_{disp} = \int_{t_0}^{t_n} v (dt) \quad [4.2]$$

Equation 4.2 was used to calculate stretch height ($h_{stretch}$, which is CM_{disp} at the instant of take-off) and flight height (h_{flight}) was calculated using the following equation:

$$h_{flight} = \frac{-(v_{TO})^2}{2g} \quad [4.3]$$

Where v_{TO} denotes take-off velocity and g is acceleration due to gravity ($-9.81\text{m}\cdot\text{s}^{-2}$).

Equation 4.3 was then used to calculate maximum CM_{disp} :

$$Max CM_{disp} = h_{stretch} + h_{flight} \quad [4.4]$$

Power (P) was calculated by multiplying absolute force and velocity at each time point, and peak power was the maximum value calculated in this way before the instant of take-off.

Mean positive power (MPP) was calculated across the positive work phase (upwards phase) using the following equation:

$$MPP = \frac{\int_{t_0}^{t_n} P(dt)}{t_{pw}} \quad [4.5]$$

Where t_{pw} denotes the length of the positive work phase.

Both peak power and mean positive power were normalised to body mass. Average rate of force development (ARFD) was calculated across the length of the active force production phase (t_{AFP}), as the average slope of the force-time curve from the start of active force production (when Fz_{net} stayed above 0 N) to the peak Fz_{net} :

$$ARFD = \frac{peak Fz_{net}}{t_{AFP}} \quad [4.6]$$

Leg press testing

Strength and power characteristics were assessed using a Keiser A420 leg press dynamometer (Keiser Sport, Fresno, CA; Figure 4.4). This equipment replaces the conventional weight stack (associated with traditional leg press testing) with pneumatic resistance and thus, reduces the effect of inertia and momentum which are inevitably large in conventional strength/power testing. The Keiser system provides force and velocity data (at 400 Hz) across each effort which can be used to calculate several force-power related variables as explained below.



Figure 4.4. Keiser leg press testing.

Before the first testing day, athletes attended a familiarisation session consisting of one 10 repetition test. At each testing session athletes performed an eight minute incremental cycle warm-up, followed by two warm-up leg press efforts from a seated position (knee angle at approximately 90°). An incremental ten repetition test was then completed from the same starting position, against low resistance in the initial repetitions and reaching an estimated ‘one repetition maximum’ resistance on the tenth repetition. Athletes were asked to extend both legs with maximum velocity on every repetition and resistance was increased until failure (some athletes performed more than 10 repetitions).

For each repetition, peak force, peak velocity and peak power were recorded for each leg. A linear trendline was plotted through the peak force - peak velocity data (Figure 4.5), as shown to be appropriate for this type of exercise (Bobbert, 2012). This linear trendline was extrapolated to the axes ($x = 0$ and $y = 0$) to yield F_{\max} and V_{\max}

(respectively) and the gradient of this line (FV_{grad}) was also recorded. A second order polynomial was fitted through the peak force - power data, the equation of which was numerically differentiated and used to calculate P_{max} and the force at P_{max} (FP_{max}). Means were calculated across both legs for all variables and F_{max} , P_{max} and FP_{max} were normalised for body mass. The reliability of this method is yet to be quantified in the scientific literature. However, pilot testing involving five talent squad athletes suggested that day-to-day variation (CV) in these Keiser output measures was 2-4%.

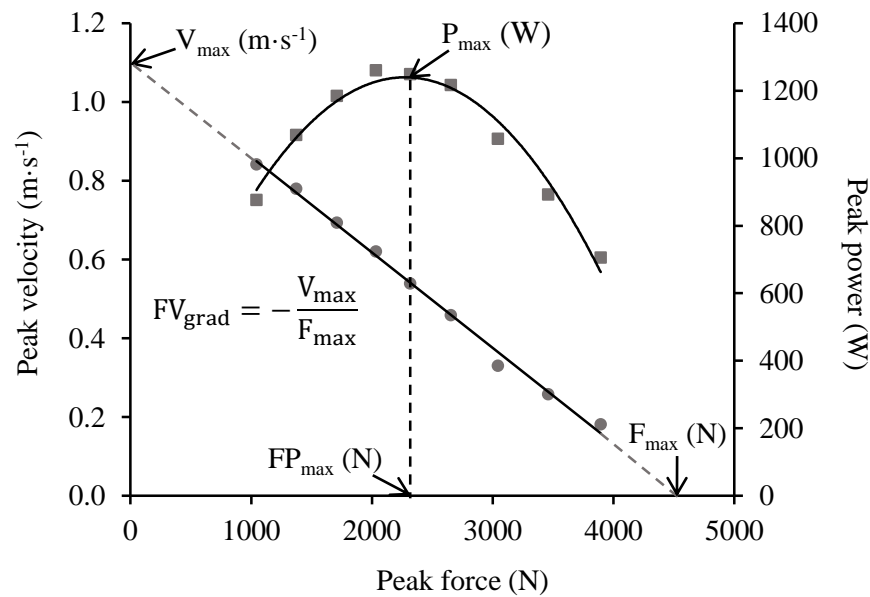


Figure 4.5. An example of the force-velocity and force-power relationships obtained and the variables calculated from the leg press testing. Grey circles and squares indicate raw force-velocity and force-power data, respectively. Solid black lines represent trendlines fitted to raw data. Grey dashed lines represent data extrapolation to obtain F_{max} and V_{max} . Black dotted lines indicate method used to calculate FP_{max} from P_{max} .

Body composition

A whole-body DXA system (Hologic Discovery W, Bedford, MA) was used to estimate body composition at a series of time points across a training season (first season for elite and second season for talent athletes). All scans took place between 0730 and 0845 hours and athletes were asked to wear light clothing with minimal reflective or metal components. Before each scan, athletes consumed a normal breakfast but were asked to complete a food diary for the preceding 24 hours and to consume 500 ml of water within the hour leading up to each scan. This was to monitor any marked changes in

dietary intake and ensure similar hydration status across scans, two of the factors known to influence DXA results (Pietrobelli et al., 1998; Nana et al., 2012). A quality control scan using a phantom spine was performed before all scanning sessions in accordance with the manufacturer's guidelines and DXA-estimated body mass was cross-validated against a scale reading (Model 880; Seca, Hamburg, Germany). Operational procedures were followed by a trained physician for the placement of the participant on the scanning bed and the regional subdivision of the scan image. Total body mass, total lean (non-bone, non-fat) mass, total fat mass, whole body fat percentage and lean leg mass were the chosen output variables.

4.2.3. Statistical analysis

At each testing session, mean values for all physical measures were calculated for each athlete. Additionally, a single mean value and standard deviation was calculated for each individual athlete across all attended testing sessions in the first training season, for each physical test score. For each athlete group (elite male, elite female, talent squad male and talent squad female), means and standard deviations for each anthropometric measure and physical test score were then also calculated. Pearson correlation coefficients were used to assess the relationships between the mean physical test scores and the mean of both push performance measures (V_{15} and V_{38-45} , from standard block position). Additionally correlations (Pearson r) were derived for the relationship between these two push performance measures. For all correlation coefficients, 90% confidence intervals (CI) were also calculated and magnitude based inferences derived as previously suggested (Batterham and Hopkins, 2006). The magnitude of the correlation coefficients were interpreted in exactly the same way as outlined in Chapter 3, section 3.2.4.

As a measure of the athletes' ability to run in a bent-over position, the ratio between sprint and push-track times was calculated between the 10 and 15 m marks for data from the second season (the only consistent splits available between the push-track and sprint tests). Additionally, the reliability of V_{15} and jump ARFD measures were assessed by calculating typical error of the measurement (in absolute terms and CV%) for all cases where athletes completed all three trials in one testing session using methods described by Hopkins (2000a). According to Smith and Hopkins (2011), TEM values should be doubled before interpreting their magnitude.

Principal component analysis (PCA) is a data reduction technique, whereby variables which are correlated with one another (but independent from other subsets of variables) are classified into factors (Tabachnik and Fidell, 2007). Thus, to explore the underlying structure and reduce the number of the physical test scores to a small set of independent factors, PCA was conducted on complete data sets from testing sessions across the first season only ($n = 59$). According to Hair et al. (2009), PCA should be conducted with at least five times as many observations as variables, however, ideally the sample-to-variable ratio should be 10:1. Additionally, regardless of the intended outcome of PCA, researchers are encouraged to consider the theoretical foundations of the variables and use judgement as to the appropriateness of the variables for inclusion in these analyses (Hair et al., 2009). Thus, only eight variables were entered into the PCA, and were carefully selected based on both the association with push performance (in the previous section) and the perceived independence from other selected variables.

The raw data for each of these chosen variables were first transformed into z-scores (centred) to standardise the scaling across all variables. The correlation matrix was then computed and assessed to confirm the suitability of the data set for PCA, using Bartlett's test of sphericity ($p < 0.05$) and the Kaiser-Meyer-Olkin measure of sampling adequacy (value > 0.5). Following this confirmation, an initial factor solution was then computed and the optimum number of factors to extract was determined using the scree test criterion. The initial factor solution was rotated using orthogonal rotation (varimax criterion) and the rotated matrix was assessed for a simplified structure. Factor loadings which exceeded ± 0.70 were considered to indicate significant loading (Hair et al., 2009). Any problematic variables (cross-loadings or non-significant loadings) were eliminated and the analysis repeated. When an acceptable factor solution was obtained, in which all variables had significant loading on a single factor, surrogate labels were assigned which were considered to best reflect the variables loaded to each component.

The two variables that were most heavily loaded to each factor were then used as prediction variables in a stepwise multiple regression analysis, in which the criterion variable was push-track performance. The use of pooled (and therefore related) data in a multiple regression analysis may result in an overly optimistic model with artificially high R^2 values due to clustering of data points or correlations between residuals. However, by definition, the number of participants in research involving elite athletes is

inherently small. Thus, to truly obtain information regarding the physical characteristics required to be an elite skeleton athlete, the methods presented here are a necessary compromise, provided that the limitations are acknowledged and tested as rigorously as possible. Accordingly, the Durbin-Watson statistic was used to assess the extent of the autocorrelation between residuals, and the consistency of these errors was evaluated using homoscedasticity and normality tests. Entered variables remained in the model if a significant R^2 (or F -ratio) change was reported. Standardised β weights allowed for the direct comparison of the relative explanatory power of the variables on the dependent variable. Finally, a regression equation was formed using the unstandardised coefficients in which physical test scores can be entered to predict start performance.

The regression model (fitted to data from the first season) was firstly cross-validated using all complete data sets obtained across the second training season ($n = 40$). Linear regression was used to assess the relationship between the predicted and actual V_{15} . The strength of the prediction was firstly assessed by comparing the R^2 values of the training and validation sets. Generally, a model can be considered stable if the R^2 decrease (so-called R^2 ‘shrinkage’) does not exceed 0.10 (Kleinbaum et al., 1988). It has been argued, however, that correlation should not be used as the primary evaluation statistic due to the ‘relative’ nature of this measure (Staudenmayer et al., 2012). Thus, standard error of the estimate (in absolute and percentage terms) was also used to provide a measure of the bias and/or precision of the model.

As the majority of athletes were included in both the training and validation data sets (first and second seasons, respectively) within this cross-validation method, the evaluation statistics may misrepresent the stability of the model. Ideally, an independent data set would be set aside and used to validate the predictive model, however, this is rarely possible in reality and especially difficult within elite sport. Thus, a further K -fold cross-validation technique was adopted to provide a more rigorous assessment of the model (Hastie et al., 2009). This method involves splitting the data into K roughly equal-sized parts, fitting a regression model to $K - 1$ parts and validating this model against the k^{th} part (the only part which was not used to ‘train’ the model). This process is then repeated for $k = 1, 2, \dots, K$. In the current study, each k^{th} part comprised data for one athlete only and therefore $K = 13$. In this way, no validation data set included data from any of the athletes who were used to create the regression model. The prediction

errors of each model were calculated for each of the K iterations and combined to provide an overall standard error of the estimate. Additionally, the correlation coefficient was computed for the relationship between the predicted and actual V_{15} , and the ' R^2 shrinkage' was evaluated as previously described.

4.3. Results

4.3.1. Anthropometry

The average (mean \pm SD) body composition measurements for each sub-group of skeleton athletes, as estimated by DXA, are provided in Table 4.4.

Table 4.4. DXA-estimated body composition data (mean \pm SD) for four athlete groups.

	Elite male athletes (n = 3)	Elite female athletes (n = 4)	Talent male athletes (n = 4)	Talent female athlete (n = 1)
Total body mass (kg)	84.0 \pm 6.9	68.3 \pm 3.0	72.6 \pm 3.9	56.3
Lean mass (kg)	69.5 \pm 6.3	52.6 \pm 2.1	63.9 \pm 3.7	44.3
Fat mass (kg)	9.9 \pm 0.6	12.3 \pm 1.6	8.7 \pm 1.2	11.0
Percentage fat (%)	12.0 \pm 1.4	18.1 \pm 1.8	12.0 \pm 1.7	19.2
Leg lean mass (kg)	24.3 \pm 2.0	18.5 \pm 0.8	21.0 \pm 1.1	14.7

N.B. Lean mass refers to non-bone, non-fat mass.

4.3.2. Physical characteristics of skeleton athletes

The average physical test scores achieved on the first and second testing days for each athlete group are provided in Table 4.5 and Table 4.6, respectively. Males scored higher than females on all physical tests, except for certain flexibility tests. The elite male squad were found to perform better than or equal to the male talent athletes on all test scores except mean countermovement jump power (under 0.5BW load), Keiser F_{\max} and Keiser FP_{\max} , each of which were recorded on the second testing day (Table 4.6). Additionally, a less negative gradient of the force-velocity curve (FV_{grad}) was exhibited for the talent squad athletes, in comparison with those in the elite squad, during the Keiser leg press test on the second day of testing. Average 10-15 m sled velocity during push-tests was 81.6 \pm 4.1% (mean \pm SD) of the upright 10-15 m mark sprint average velocity. The elite squad achieved 83.1 \pm 3.8% (mean \pm SD) of their upright sprint velocity when pushing the sled, whereas the talent squad achieved 79.9 \pm 4.0%.

Table 4.5. Physical test scores (mean \pm SD) achieved by each group of skeleton athletes on the first testing days.

Physical performance variable	Elite squad		Talent squad	
	Male athletes	Female athletes	Male athletes	Female athletes
<u>Push-track tests</u>				
Sled velocity at 15 m ($\text{m}\cdot\text{s}^{-1}$)	7.61 \pm 0.17	6.91 \pm 0.19	7.40 \pm 0.16	6.73
Sled velocity 38-45 m ($\text{m}\cdot\text{s}^{-1}$)	10.87 \pm 0.11	10.09 \pm 0.14	10.49 \pm 0.17	9.87
<u>Sprint tests</u>				
Unresisted time to 15 m (s)	2.43 \pm 0.10	2.67 \pm 0.05	2.43 \pm 0.03	2.69
Unresisted 15 - 30 m time (s)	1.66 \pm 0.07	1.84 \pm 0.04	1.67 \pm 0.04	1.84
Resisted time to 15 m (s)	2.58 \pm 0.13	2.93 \pm 0.09	2.79 \pm 0.06	3.14
Resisted 15 - 30 m time (s)	1.92 \pm 0.08	2.14 \pm 0.05	1.95 \pm 0.04	2.21
<u>Flexibility tests</u>				
KEA 90° (°)	163 \pm 5	164 \pm 6	N/A	N/A
KEA 110° (°)	143 \pm 5	145 \pm 7	N/A	N/A
Sit and reach test (cm)	32 \pm 8	27 \pm 2	32 \pm 4	37

Table 4.6. Physical test scores (mean \pm SD) achieved by each group of skeleton athletes on the second testing days.

Physical performance variable	Elite squad		Talent squad	
	Male athletes	Female athletes	Male athletes	Female athletes
<u>Vertical jump tests</u>				
Max CM _{disp} - 0 kg load (m)	0.62 \pm 0.04	0.49 \pm 0.06	0.60 \pm 0.02	0.43
Max CM _{disp} - 5 kg load (m)	0.60 \pm 0.05	0.46 \pm 0.05	0.59 \pm 0.04	0.41
Max CM _{disp} - Barbell load (m)	0.50 \pm 0.04	0.40 \pm 0.05	0.46 \pm 0.03	0.36
Max CM _{disp} - 0.5 BW load (m)	0.39 \pm 0.06	0.30 \pm 0.04	0.39 \pm 0.03	0.28
Peak power - 0 kg load (W·kg ⁻¹)	68.9 \pm 3.6	57.2 \pm 6.6	68.1 \pm 4.1	54.9
Peak power - 5 kg load (W·kg ⁻¹)	67.8 \pm 4.1	56.1 \pm 5.8	67.7 \pm 4.3	55.0
Peak power - Barbell load (W·kg ⁻¹)	65.1 \pm 4.5	53.9 \pm 6.2	64.0 \pm 3.8	52.8
Peak power - 0.5 BW load (W·kg ⁻¹)	63.5 \pm 5.5	52.2 \pm 6.5	63.2 \pm 4.1	52.1
Mean power - 0 kg load (W·kg ⁻¹)	38.4 \pm 2.0	31.5 \pm 3.8	37.7 \pm 2.6	31.3
Mean power - 5 kg load (W·kg ⁻¹)	36.3 \pm 2.4	29.1 \pm 3.3	35.9 \pm 2.3	29.8
Mean power - Barbell (W·kg ⁻¹)	34.6 \pm 1.8	27.4 \pm 3.9	33.9 \pm 2.3	29.2
Mean power - 0.5BW load (W·kg ⁻¹)	32.7 \pm 2.3	25.4 \pm 3.7	32.8 \pm 2.3	27.9
ARFD - 0 kg load (kN·s ⁻¹)	6.83 \pm 1.95	5.00 \pm 1.38	5.56 \pm 1.53	5.29
ARFD - 5 kg load (kN·s ⁻¹)	6.27 \pm 1.32	3.71 \pm 0.80	4.09 \pm 0.50	4.14
ARFD - Barbell load (kN·s ⁻¹)	5.01 \pm 2.05	2.53 \pm 0.46	3.43 \pm 0.94	4.00
ARFD - 0.5BW load (kN·s ⁻¹)	3.41 \pm 1.71	1.64 \pm 0.46	2.65 \pm 0.40	2.78
<u>Keiser leg press tests</u>				
Keiser F _{max} (N·kg ⁻¹)	75.6 \pm 1.9	67.6 \pm 2.6	82.3 \pm 9.4	74.1
Keiser V _{max} (m·s ⁻¹)	1.17 \pm 0.07	1.00 \pm 0.11	1.04 \pm 0.10	0.87
Keiser P _{max} (W·kg ⁻¹)	21.4 \pm 2.2	16.4 \pm 1.8	20.4 \pm 1.3	15.9
Keiser FP _{max} (N·kg ⁻¹)	38.0 \pm 1.6	33.9 \pm 1.7	43.1 \pm 4.8	37.8
Keiser FV _{grad} ($\cdot 10^{-4}$)	-1.9 \pm 0.2	-2.2 \pm 0.3	-1.8 \pm 0.3	-2.1

4.3.3. Relationships between physical characteristics and push performance

A strong positive association was found between V₁₅ and V₃₈₋₄₅ ($r = 0.97$, 90% CI = 0.91 to 0.99). Additionally, many physical performance variables were found to be strongly related to both V₁₅ (Figure 4.6) and V₃₈₋₄₅ (Figure 4.7).

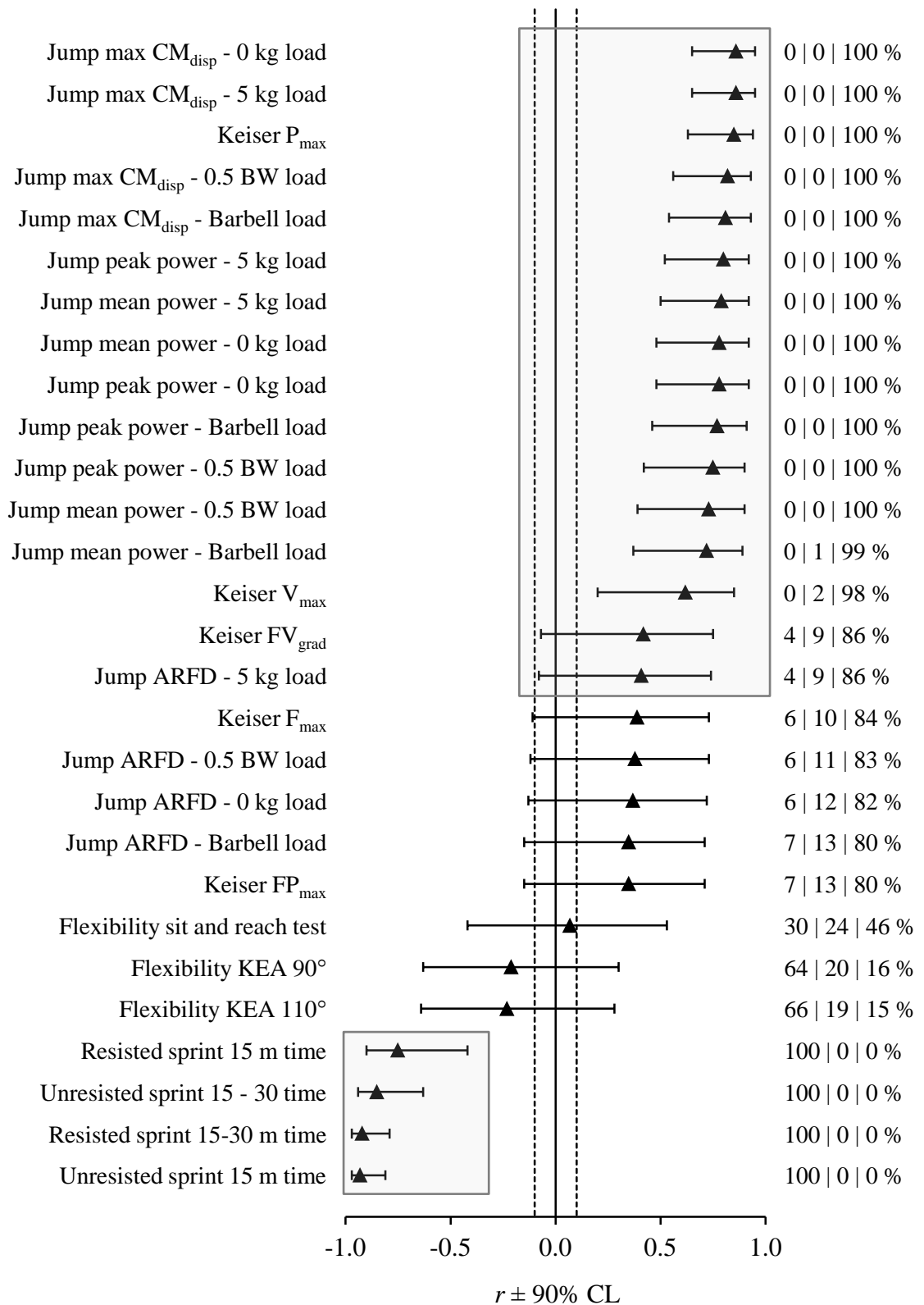


Figure 4.6. Pearson correlation coefficients ($\pm 90\%$ CI) between 15 m sled velocity and physical test scores. Central area ($r = 0.0 \pm 0.1$) indicates a trivial relationship. Percentages in brackets represent the likelihoods that the effect is negative | trivial | positive. Grey boxes indicate variables with clear relationships.

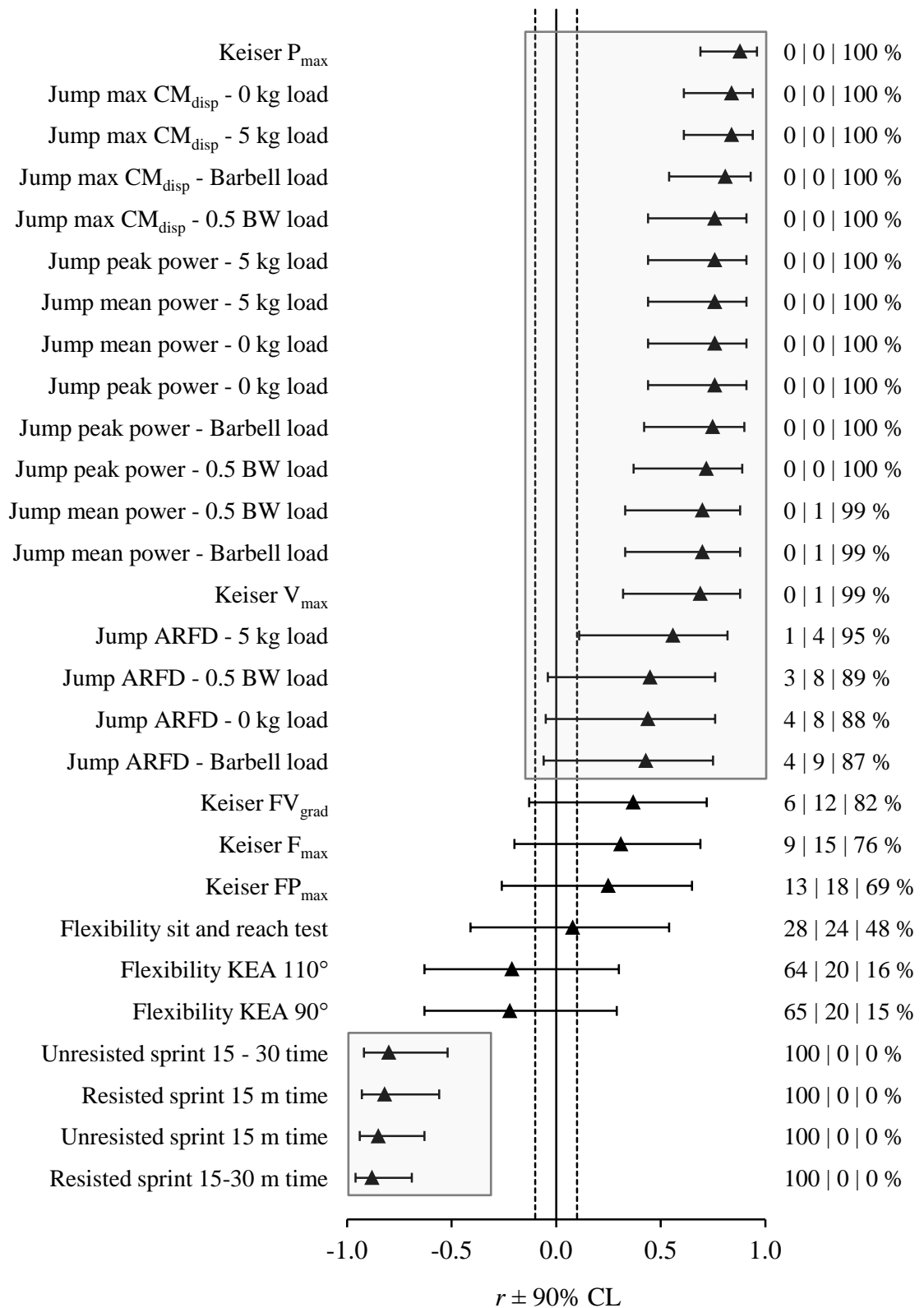


Figure 4.7. Pearson correlation coefficients ($\pm 90\%$ CI) between 38 - 45 m sled velocity and physical test scores. Central area ($r = 0.0 \pm 0.1$) indicates a trivial relationship. Percentages in brackets represent the likelihoods that the effect is negative | trivial | positive. Grey boxes indicate variables with clear relationships.

The physical performance variables that were most strongly related to push performance were sprint performance measures. Specifically, the strongest relationships were observed between push performance measures (V_{15} and V_{38-45}) and unresisted sprint time to 15 m and resisted sprint 15 - 30 m time, as shown in Figure 4.8.

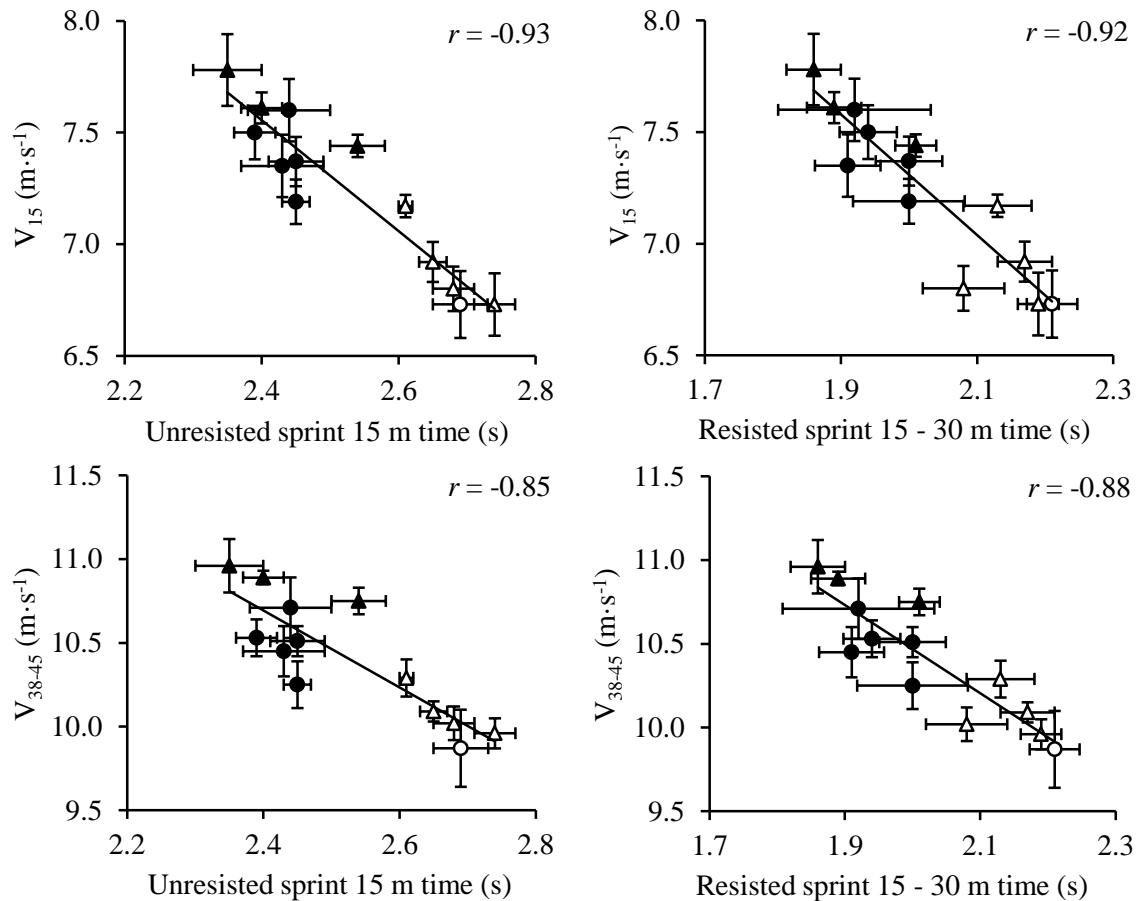


Figure 4.8. Relationships between sprint and push performance measures (mean \pm SD) across the first training season. White symbols = female athletes, black symbols = male athletes, circular symbols = talent squad athletes, triangular symbols = elite squad athletes. V_{15} = 15 m sled velocity. V_{38-45} = 38-45 m average sled velocity.

Clear relationships were observed between both of the push performance measures and maximum CM_{disp} , peak power and mean power during vertical jump tests under all four loads. Vertical jump scores under the lighter loads (0 kg and 5 kg) were more strongly related to both V_{15} and V_{38-45} than those in the heavier load conditions (barbell and 0.5 BW). Maximum CM_{disp} was found to be more strongly related to push performance measures than the jump peak power and mean power under the same load. Figure 4.9 illustrates the relationships between maximum CM_{disp} and push performance.

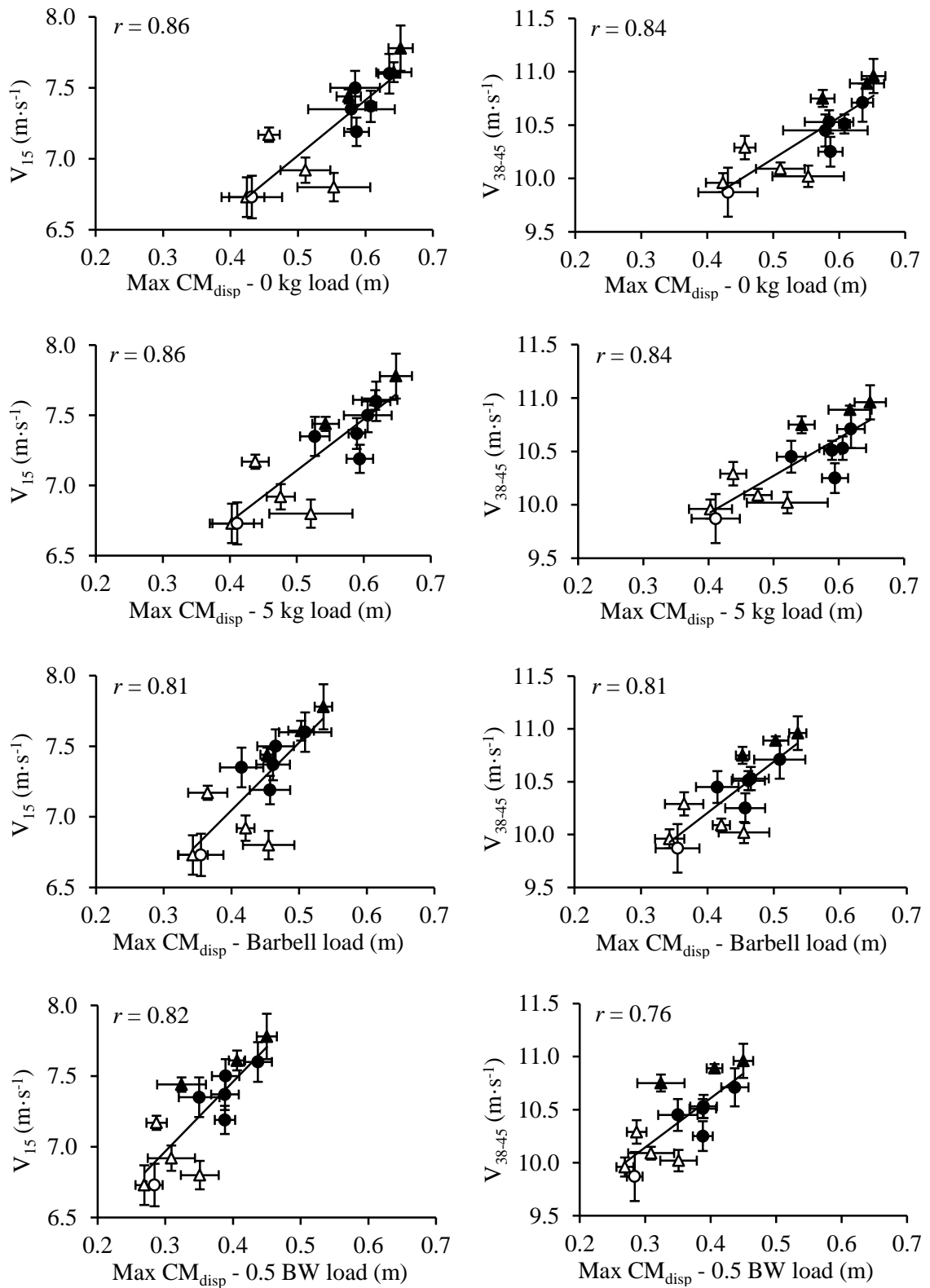


Figure 4.9. Relationships between vertical jump and push performance measures (mean \pm SD) across the first training season. White symbols = female athletes, black symbols = male athletes, circular symbols = talent squad athletes, triangular symbols = elite squad athletes. V₁₅ = 15 m sled velocity. V₃₈₋₄₅ = 38-45 m average sled velocity.

Two Keiser leg press outcome variables (P_{\max} and V_{\max}) were found to be strongly, positively related to both V_{15} and V_{38-45} . Conversely, unclear relationships were reported between push performance and flexibility measures (Figure 4.6 and Figure 4.7). The typical error of the measurement (mean \pm 90% confidence intervals) for V_{15} and ARFD measurements were $0.10 \pm 0.02 \text{ m}\cdot\text{s}^{-1}$ ($1.4 \pm 0.1\%$) and $0.97 \pm 0.06 \text{ kN}\cdot\text{s}^{-1}$ ($29.4 \pm 2.3\%$), respectively.

Total body mass was positively related to both V_{15} ($r = 0.70$, 90% CI = 0.31 to 0.89) and V_{38-45} ($r = 0.78$, 0.46 to 0.92). Total lean mass was also found to be positively related to both push performance measures ($r = 0.78$, 90% CI = 0.46 to 0.92 for V_{15} ; $r = 0.83$, 0.56 to 0.94 for V_{38-45}). Additionally, clear positive relationships were observed between leg lean mass and both V_{15} ($r = 0.79$, 90% CI = 0.48 to 0.92) and V_{38-45} ($r = 0.84$, 0.59 to 0.94). In contrast, clear negative relationships were found between total fat mass and both V_{15} ($r = -0.58$, 90% CI = -0.11 to -0.84) and V_{38-45} ($r = -0.51$, -0.01 to -0.80). Total body fat percentage was also negatively related to both push performance measures ($r = -0.78$, 90% CI = -0.46 to -0.92 for V_{15} ; $r = -0.76$, -0.42 to -0.91 for V_{38-45}).

4.3.4. The underlying structure amongst physical test scores

Eight variables which were found to be strongly related to push performance and/or were perceived to represent different aspects of physical ability were identified and entered into the PCA. These included unresisted sprint 15 m time, resisted sprint 15-30 m time, jump max $CM_{\text{disp}} - 0 \text{ kg}$ load, jump max $CM_{\text{disp}} - 5 \text{ kg}$ load, Keiser F_{\max} , Keiser P_{\max} , Keiser V_{\max} and Keiser FP_{\max} . Two of these variables, Keiser P_{\max} and V_{\max} , were found to be cross-loaded (equally loaded to two or more components) and thus were eliminated from the data set and the analysis was then repeated with the six remaining variables. Bartlett's test of sphericity ($p = 0.00$) and the Kaiser-Meyer-Olkin measure of sampling adequacy (0.74) were used to confirm that the remaining variables were sufficiently correlated and the data were appropriate for this type of analysis.

Three components were derived from this analysis, explaining a total of 97.2% of the total variance in the data (Table 4.7). The first component (comp1) accounted for a large proportion of the variance in the data (35.7%) and, based on the associated variables, was interpreted as a component indicating sprint ability. The second component

(comp2) accounted for a similar amount of the variance (34.5%) in the data set, and was associated with measures of maximum strength (force-power characteristics). The third component (comp3) accounted for 27.0% of the variance in the data set and was interpreted to represent lower limb power, as the variables most heavily loaded to this component were the two variables relating to maximum CM displacement during vertical jumps.

Table 4.7. Principal component analysis output.

	comp1	comp2	comp3
Variance explained	35.7%	34.5%	27.0%
Unresisted sprint 15 m time	0.869	-0.304	-0.347
Resisted sprint 15 – 30 m time	0.866	-0.121	-0.439
Jump max CM _{disp} – 0 kg load	-0.507	0.292	0.801
Jump max CM _{disp} – 5 kg load	-0.558	0.283	0.765
Keiser F _{max}	-0.186	0.942	0.219
Keiser FP _{max}	-0.184	0.954	0.179

N.B. Bold values indicate the component to which each variable was most heavily loaded to.

4.3.5. *The formation of a predictive model*

The variable which was found to be most heavily loaded to each component was considered to best represent that component and was used in the subsequent multiple regression analysis. Thus, unresisted sprint 15 m time, Keiser FP_{max} and jump max CM_{disp} – 0 kg load were entered into a stepwise multiple regression model as the predictor variables, and V₁₅ was the criterion variable. The choice of criterion variable was based on the fact that stronger relationships (higher *r* values) were exhibited between V₁₅ and the three factors identified by the PCA, than those between V₃₈₋₄₅ and the three factors.

A Durbin-Watson statistic of 1.33 indicated some autocorrelation between residual errors, however, it has been suggested that values below 1 or above 3 are indicative of excessive autocorrelation (Field, 2000). In addition to this statistic, homoscedasticity tests and normality tests were used to further test whether the assumptions of the model have been met. The *ZRESID vs. *ZPRED plots revealed consistency of residual errors, with no evidence for heteroscedasticity or clustering of the residuals. Furthermore, the normality plots revealed that the residuals were normally distributed.

Thus, the data appeared to conform to the assumptions of multiple regression analysis. All three independent variables were found to significantly contribute to the regression model, with significant F -ratio (R^2) changes observed when each variable was entered (Table 4.8). Overall, the model was found to explain 86.1% of the variance in V_{15} , with 81%, 3% and 2% of the variance explained by unresisted sprint 15 m time, jump max $CM_{disp} - 0\text{kg}$ load and Keiser FP_{max} , respectively.

Table 4.8. Regression model summary.

Model	Variables entered	R	R^2	Change statistics		
				R^2 change	F change	Sig.
1	Unresisted sprint 15 m time	0.899	0.807	0.807	238.889	0.000
2	Jump max $CM_{disp} - 0\text{ kg}$ load	0.916	0.838	0.031	10.654	0.002
3	Keiser FP_{max}	0.928	0.861	0.023	9.127	0.004

The regression coefficients for each variable are provided in Table 4.9. Standardised coefficients (β weights) indicate that unresisted sprint 15 m time has greater relative predictive power for V_{15} compared with jump max $CM_{disp} - 0\text{ kg}$ load and Keiser FP_{max} (-0.712 vs. 0.347 and -0.181, respectively).

Table 4.9. Regression coefficients for model 3.

	Unstandardised coefficients	Standardised coefficients	t value	Sig.
Constant	11.530		14.991	0.000
Unresisted sprint 15 m time	-1.866	-0.712	-8.208	0.000
Jump max $CM_{disp} - 0\text{ kg}$ load	0.015	0.347	4.013	0.000
Keiser FP_{max}	-0.011	-0.181	-3.021	0.004

The unstandardised β weights (coefficients) can then be used to form the following regression equation (4.7), in which variables can be entered and V_{15} predicted:

$$V_{15} = (-1.868 \times \text{Unres. sprint 15 m time}) + (0.015 \times \text{MaxCM}_{disp} 0\text{ kg}) \\ - (0.011 \times FP_{max}) + 11.53$$

[4.7]

4.3.6. Validating the predictive model

A strong relationship ($r = 0.90$, 90% CI = 0.83 to 0.94; $R^2 = 0.81$) between actual and predicted V_{15} was observed when the model was evaluated using data from the second season. This can be compared with the original regression model (fitted to data from the first season) which explained 86% of the variance ($R^2 = 0.86$). Thus, R^2 value ‘shrinkage’ of 0.05 (relating to 5% of the explained variance) was observed between the original and validation data set. The standard error of the estimate (SEE) increased when the regression equation was applied to the second season’s data, compared with when it was applied to data from the first season ($0.20 \text{ m}\cdot\text{s}^{-1}$ and 2.48% vs. $0.13 \text{ m}\cdot\text{s}^{-1}$ and 1.52%, respectively). When the K -fold validation technique was used to evaluate the model, a similarly strong relationship between predicted and actual V_{15} was observed ($r = 0.88$, 90% CI = 0.82 to 0.92; $R^2 = 0.77$) and therefore ‘ R^2 shrinkage’ of 0.09 (or 9% of the explained variance) was observed. Consequently, the SEE were inflated to a small degree when the model was applied in the K -fold validation method than in the original model ($0.17 \text{ m}\cdot\text{s}^{-1}$ and 1.97% vs. $0.13 \text{ m}\cdot\text{s}^{-1}$ and 1.52%, respectively).

4.4. Discussion

The purpose of this study was to understand which physical characteristics are fundamental to a fast skeleton start. A series of multivariate analyses were conducted to identify and validate a set of three independent predictors of start performance (15 m sled velocity). These variables were unresisted sprint 15 m time, jump max $\text{CM}_{\text{disp}} - 0 \text{ kg}$ load and Keiser FP_{max} , highlighting the importance for skeleton athletes to develop high sprint ability, explosive power and a more ‘velocity-oriented’ power profile.

A large number of physical test scores were strongly related to push performance (both V_{15} and V_{38-45}) and therefore appear to be valid tools in which to monitor skeleton start training. The relationships between all physical test scores and push performance were assessed using the pooled data set (i.e. combining data from male and female athletes). Naturally, there were sex differences in both the physical test scores and push performance and there appeared to be some clustering of data points between certain measures (for example unresisted 15 m sprint time and 15 m sled velocity; Figure 4.8). However, when the aforementioned association was assessed for males and females

separately, linear relationships were still observed ($r = -0.55$ and $r = -0.91$, respectively). Thus, the covariance between these variables does not seem to differ across sexes. Although in some cases the correlation coefficients may be slightly inflated, the pooling of data was not anticipated to change the interpretation of these relationships.

Sprint performance measures were the most strongly related variables to push performance with faster sprint times associated with higher sled velocities. Jump height and peak power under 0 kg and 5 kg loads were the next strongest related variables, perhaps suggesting that power production under lighter loads (and therefore higher velocities) is of potentially greater importance to push performance than under heavier loads (and lower velocities). The associations between start performance and sprint and jump test measures are consistent with those previously shown amongst US skeleton (Sands et al., 2005) and bobsleigh (Osbeck et al., 1996) athletes, and confirm that the faster sprinters and more powerful vertical jumpers tend to be faster starters during the push-track tests. In fact, the successful athletes from an Australian skeleton talent identification programme (the four female athletes eventually chosen to represent Australia in World Cup competitions) were those who recorded faster 30 m sprint times and higher unloaded jump powers compared with the group average (26 athletes) at the initial screening phase (Bullock et al., 2009a). Thus, collectively these findings suggest these tests to be key indicators of an athlete's chances of success in skeleton.

There have been mixed findings regarding the relationship between measures of maximum muscular strength and explosive performance (Anderson et al., 1991; Nesser et al., 1996; Dowson et al., 1998). Specifically, it has been suggested that maximum strength under heavy loads (and therefore low velocities) has limited application to dynamic, explosive movements (Anderson et al., 1991). In fact, Morin et al. (2012) found faster sprinters to elicit a more 'velocity-oriented' force-velocity profile, obtained using an instrumented treadmill across a six second maximal sprint. Additionally, the same study reported a strong positive association ($r = 0.74$) between 100 m sprint performance and theoretical maximal horizontal velocity (a measure which is comparable with V_{\max} in this study) but a weaker relationship with theoretical maximum horizontal force ($r = 0.45$) was also reported. In a similar way, it appears that high contraction velocity (V_{\max}) is a more important determinant of start performance in this

group of skeleton athletes ($r = 0.62$) than maximum force production (F_{\max} ; $r = 0.39$). This notwithstanding, out of all the Keiser variables, peak power (P_{\max}) was found to be a strongest predictor ($r = 0.85$) of push performance (V_{15}). Thus, the product of F_{\max} and V_{\max} (i.e. P_{\max}), which reflects the interaction between strength and speed characteristics in one measure, appears to be of greater importance than the discrete variables alone, as previously suggested for explosive movements (Cronin and Hansen, 2005).

Average rate of force development (ARFD) during countermovement jumping (in three of the loading conditions) was not related to V_{15} . This finding is in agreement with a previous study of US National skeleton athletes (Sands et al., 2005) but may be surprising considering the widely acknowledged importance of ARFD to explosive muscular contraction (Aagaard et al., 2002a; Tillin et al., 2010). However, poor test-retest reliability ($CV = 29.4\%$) of ARFD during countermovement jumping may have confounded the results and masked any potential correlation between ARFD and start performance. Thus, this jump performance measure should perhaps be used with caution, as previously advocated (McLellan et al., 2011). Hamstring flexibility test scores also do not appear to be important predictors of skeleton start performance, with unclear relationships reported for all three tests (r ranged from -0.23 to 0.07). In fact, a negative associations have previously been reported between flexibility measures and running performance, which is suggested to be due to the influence of musculotendinous stiffness on storage and return of elastic energy (Craib et al., 1996). An alternative explanation could be that static flexibility tests (such as those conducted in this study) do not provide an appropriate reflection of the musculoskeletal requirements in dynamic situations.

Generally, it is likely that some of the physical tests conducted as part of a monitoring programme are essentially measuring the same aspect of performance, potentially reducing the efficiency of this process. For this reason, principal component analysis was used in this study to extract three independent and underlying components (sprint ability, lower limb power and strength) which were then entered into the multiple regression analysis. Each of these variables was found to significantly contribute to the regression model (overall the model explained 86% of the variance in V_{15}). Thus, not only were these variables independent of each other but each of these was found to improve the prediction of skeleton start performance. Sprint performance explained the

largest portion of the variance (81%) in push performance. Although the relative contributions to the prediction are small, maximum CM_{disp} (unloaded jump) and force-power characteristics (Keiser FP_{max}) both made significant contributions (3 and 2%, respectively) to the prediction and the associated tests are therefore important inclusions in the physical test battery. Interestingly, the force at peak power (Keiser FP_{max}) negatively contributed to the model, indicating that achieving peak power under lighter loads is more important to skeleton start performance than that under higher loads. This finding also reinforces the notion that a more ‘velocity-oriented’ force-velocity profile is advantageous in skeleton.

From these multivariate analyses, a regression equation was formed using the unstandardised correlation coefficients and this was firstly cross-validated using data from the following season. There was some evidence of the model over-fitting the data, with higher prediction errors observed in the validation data set compared with the training data set (0.20 vs. 0.13 $m \cdot s^{-1}$ or 2.48 vs. 1.52%, respectively). This is a typical observation when cross-validating a regression model (Tabachnik and Fidell, 2007), however, the decrease in R^2 (0.05) was, importantly, within the acceptable threshold of 0.10 (Kleinbaum et al., 1988). Additionally, the inflated prediction errors were still found to be equal to the typical error observed in the V_{15} measurement (0.20 $m \cdot s^{-1}$), and thus, seem to be within acceptable limits. The K -fold validation technique was adopted to eliminate the dependency between training and validation data sets and to provide a more robust evaluation of the regression model’s predictive power when applied more broadly (Hastie et al., 2009). The model was also found to be stable using this novel method, with only small R^2 shrinkage (0.09) and a small increase in the prediction errors from when the model was originally fitted (0.17 vs. 0.13 $m \cdot s^{-1}$ or 1.97 vs. 1.52%, respectively). Thus, both validation techniques suggest that the model can provide an accurate and sufficiently stable prediction of push performance from just three variables. This has clear implications for the monitoring of current skeleton athletes, but can also play an important role in talent identification schemes.

Principal component analysis has previously been used to extract independent factors relating to vertical jumping ability, which were shown by Sands et al. (1999) to differentiate the physical ability levels amongst a group of gymnasts. However, few studies (Mermier et al., 2000; Douda et al., 2008) have combined multivariate analyses

in the same way as this study to fully evaluate the physical requirements of sports (climbing and gymnastics, respectively). In these previous studies, multiple factors were extracted from PCA, however, few were found to significantly contribute to the prediction of the criterion performance measure (three factors with one significant contributor and six factors with two significant contributors, respectively). Moreover, the overall predictive power of these previous regression models was found to be lower than that of the current model for skeleton start performance ($r = 0.77$ and 0.74 vs. 0.93 , respectively). Thus, it could be that the technical, tactical and/or psychological components of the other sports may be larger than in the skeleton start. If overall athlete progress is being monitored rather than simply the physical development, such components require inclusion in the predictive models.

Overall, the physical tests conducted in this study were found to provide a valid reflection of a skeleton athlete's current training status. However, it should be noted that, it is currently unknown whether the accuracy of this prediction would be compromised if only the key tests are performed. For example, if tests are not completed in the same sequence, with the same number of repetitions and the same recovery periods, it is currently unknown whether the predictive model would be as stable as demonstrated in this study. For a series of physical tests like these, fatigue is likely to influence the scores achieved, particularly on the second testing day. Thus, future work could quantify this effect and reassess the strength of the associations and the predictive power of the model, when a smaller set of key tests are conducted.

It is well established that lean (specifically muscle) mass is the only contributor to force production (Maughan et al., 1983; Bruce et al., 1997). This provides an explanation for the positive relationships reported previously between lean mass and sprint performance (Perez-Gomez et al., 2008), as well as associations between push performance and both lean mass ($r \pm 90\% \text{ CI} = 0.78 \pm 0.23$) and leg lean mass ($r = 0.79 \pm 0.22$) in the current study. Conversely, adipose tissue can be considered 'passive' soft tissue mass as it cannot produce force. In the current study, superior push performances were associated with both lower total fat mass ($r \pm 90\% \text{ CI} = -0.58 \pm 0.36$) and body fat percentage ($r = -0.78 \pm 0.23$). Thus, a more favourable body composition profile for skeleton start performance is, logically, one with more lean mass and leg lean mass, and less adipose tissue. The body composition changes exhibited by skeleton athletes in response to

training, and the subsequent impact on performance, will be discussed in a later section (Chapter 6).

The skeleton athletes involved in the current study appear to exhibit similar fat percentages to the US National skeleton athletes characterised previously (Sands et al., 2005): 12.0 vs. 12.5% for male athletes, respectively and 18.1 vs. 18.0% for female athletes, respectively. Direct comparisons between these findings are problematic due to the differences between body composition estimation methods used (DXA scanning vs. skinfold measurements). Although high correlations between percentage fat values calculated using these two methods have been reported (Pritchard et al., 1993), percentage fat estimated by DXA has been shown to be systematically higher than that estimated from skinfold measurements (Gutin et al., 1996; van der Ploeg et al., 2003). Thus, the real mean fat percentages of the athletes in the current study are likely to be lower than those previously studied (Sands et al., 2005). A range of somatotypes was previously reported in the past US skeleton squad (Sands et al., 2005) and a larger standard deviation for body fat percentage was also observed, compared with the current study. This may provide some support for the convergence of body composition towards a more uniform physique, as the sport of skeleton has matured.

Anthropometric measurements were found to differ between sexes and squads (male squad comparisons only). Inter-squad comparisons for female athletes were considered inappropriate because there was only one female talent squad athlete. Elite male athletes tended to be taller and have greater total mass, lean mass and lean leg mass than the talent squad male athletes. Interestingly, male elite and male talent squad athletes were found to exhibit similar DXA-estimated body fat percentages. Thus, although male elite athletes had greater lean mass in absolute terms than their less experienced counterparts, the relative composition of body mass was similar. This finding is in contradiction to a previous study by Callister et al. (1991) in which inter-squad differences in body composition were observed in judo athletes. However, as judo is a weight-class sport, body composition (particularly body fat percentage) should perhaps be expected to differentiate performance levels to a greater extent than in skeleton.

Given the association between muscle cross-sectional area and indices of both strength and power (Bruce et al., 1997), similar relative strength and power may, therefore, be

expected for the male elite and male talent squad skeleton athletes in the current study. Indeed, jump testing revealed that relative peak power outputs of elite squad male athletes were only between 0.15 and 1.72% higher than those for male talent squad athletes across all loading conditions. The power-to-body mass ratio is considered to be a key predictor of explosive performances (Cronin and Hansen, 2005) and thus, may also partly explain the almost identical unresisted sprint times achieved by male elite squad (2.43 ± 0.10 s and 1.66 ± 0.07 s for 15 m and 15-30 m times, respectively) and talent squad (2.43 ± 0.03 s and 1.67 ± 0.04 s, respectively) athletes. However, there were discrepancies in push performance between squads (mean $V_{15} \pm SD$ was 7.61 ± 0.17 and 7.40 ± 0.16 m·s⁻¹ for male elite and male talent squad athletes, respectively) which can be attributed to other factors which are likely to influence skeleton start performance, such as bent-over running technique (particularly on the declined surface). In fact, elite squad athletes were found to achieve push velocities which were 83.1% of the upright running velocity, compared with 79.9% for talent squad athletes.

Elite squad athletes were found to perform better than talent squad athletes on almost all physical tests, probably reflecting a more extensive training history and thus, more advanced musculoskeletal development. Interestingly, talent athletes (both female and male) were found to exhibit higher relative strength (Keiser F_{max} expressed per kg mass) than their elite counterparts (Table 4.6). Conversely, maximum contractile velocity (Keiser V_{max}) was found to be higher in the elite compared with the talent squad, for both male (1.17 ± 0.07 vs. 1.04 ± 0.07 m·s⁻¹, respectively) and female (1.00 ± 0.11 vs. 0.87 m·s⁻¹, respectively) athletes. Thus, force-velocity characteristics appear to differentiate performance levels amongst this group. This somewhat supports the previous observation that the ability for the lower limbs to contract quickly may differentiate performance levels to a greater extent than the ability to contract forcefully. This could be related to the requirement for skeleton athletes to attain high step frequencies (as shown in Chapter 3) and exert high forces over short contact phases when sprinting at high velocity on a declined gradient (Weyand et al., 2000).

The physical profiles presented in this study revealed this group of skeleton athletes as powerful individuals with the current athletes outperforming the nationally ranked power lifters, Olympic lifters and sprinters assessed by McBride et al. (1999) and Hennessy and Kilty (2001). Countermovement jump powers under 0 kg load for elite

and talent squad male skeleton athletes were found to be superior to those of the elite male power lifters, Olympic lifters and sprinters (68.9 and 68.1 $\text{W}\cdot\text{kg}^{-1}$ vs. 56.9, 63.0 and 63.8 $\text{W}\cdot\text{kg}^{-1}$, respectively) tested by McBride et al. (1999) using the same methods as the current study. Moreover, unresisted 30 m sprint times for the female skeleton athletes were found to be faster than those reported for the nationally ranked sprint athletes (4.50 and 4.53 s for female elite and talent athletes, respectively vs. 4.58 s) studied by Hennessy and Kilty (2001) using the same methods as the current study (i.e. touchpad initiation). Additionally, athletes in the current study exhibited faster 15-30 m unresisted sprint times than the US National skeleton athletes (1.66 and 1.67 s vs. 1.79 s for elite and talent male athletes, respectively; 1.84 s for all female athletes vs. 2.13 s) previously studied by Sands et al. (2005) using the same data collection methods.

Countermovement jump height scores are seldom directly comparable across studies due to a wide range of jump height calculation methods adopted. The previous study involving US skeleton athletes (Sands et al., 2005) used flight time to calculate jump height, whereas the maximum CM displacement measurements in the current study include stretch height (CM displacement from standing position to take-off position) which does not form part of the flight time calculations (Aragón-Vargas, 2000). Thus, the greater jump heights (max CM_{disp}) reported in this study compared with the previous study by Sands et al. (0.62 and 0.60 m vs. 0.45 m for elite and talent male athletes, respectively; 0.49 and 0.43 m vs. 0.33 m for elite and talent female athletes, respectively) may be partly explained by this methodological discrepancy. However, as stretch heights were 0.09 ± 0.02 m (mean \pm SD) in the current study, it does appear that the skeleton athletes involved in this study could achieve superior vertical jump performances than those previously studied by Sands et al. (2005). In fact, peak jump power is directly comparable with the previous study and higher peak power values (0 kg jump) were observed for the athletes in the current study (68.9, 68.1, 57.2 and 54.9 $\text{W}\cdot\text{kg}^{-1}$ for male elite, male talent, female elite and female talents athletes, respectively) compared with the US National skeleton athletes (54.3 and 39.4 $\text{W}\cdot\text{kg}^{-1}$ for male and female athletes, respectively; Sands et al., 2005). Additionally, male athletes in the current study were found to be more powerful on average when jumping with the 20 kg load (65.1 and 64.0 $\text{W}\cdot\text{kg}^{-1}$ for elite and talent athletes respectively), compared with the US male athletes (60.3 $\text{W}\cdot\text{kg}^{-1}$; Sands et al. 2005).

It is acknowledged that variation in testing schedules could result in different levels of fatigue, potentially introducing discrepancies and masking the true differences between populations. However, collectively, these findings reveal marked differences between the physical abilities of the current athletes involved in this study and the US skeleton athletes tested previously (Sands et al., 2005), perhaps indicating differences in training histories and emphases between squads. These findings also provide some evidence for the advancement of physical capabilities of competitive skeleton athletes in recent times. As previously speculated (Bullock et al., 2008), this could be a consequence of an increase in the importance of the push-start phase to overall performance as the sport of skeleton matures. It may now be that a powerful start has more of an influence on the race outcome, or at least is perceived to have more of an influence, than it did almost 10 years ago when the previous study (Sands et al., 2005) was published.

4.4.1. Conclusion

This chapter used a series of multivariate tests to reveal three variables which underpin push performance, each of which significantly contributed to the prediction of push performance. Using a data set from the following season as well as the novel *K*-fold validation technique, it was demonstrated that these three variables can provide an accurate and stable prediction of skeleton start performance. Importantly, this study introduced a process through which to evaluate testing batteries and could therefore improve the efficiency of talent identification and athlete monitoring protocols. Additionally, this chapter has provided an overview of the physical characteristics exhibited by competitive skeleton athletes. This group were presented as power-based athletes and there was some evidence for the physical advancement of skeleton athletes across the past decade.

CHAPTER 5: BIOCHEMICAL RESPONSES AND THE INFLUENCE OF TESTOSTERONE ON START PERFORMANCE AND LEAN MASS CHANGE IN SKELETON ATHLETES

5.1. Introduction

When evaluating the progress of a training programme, sports scientists and coaches implement various monitoring protocols and testing methods in an attempt to obtain valid and reliable insights into the current state of an athlete. The findings from Chapter 4, for example, demonstrated that a small battery of physical tests can provide an accurate indication of a skeleton athlete's training progress. In addition to the more conventional modes of athlete monitoring, a range of biochemical tests are now available which have the potential to provide further information regarding the physiological status of athletes.

Various hormonal and metabolic markers can be assessed using blood, saliva or urine sampling, some of which can be indicative of an athlete's capacity (or incapacity) to train or perform (Urhausen et al., 1995; Viru and Viru, 2001; Cook and Crewther, 2012; Crewther et al., 2012b). For example, high concentrations of the enzyme creatine kinase (CK) are found within muscle fibres and exercise-induced increases in serum CK have been widely documented, particularly following eccentric exercise (Byrnes et al., 1985; Wolf et al., 1987; Clarkson and Tremblay, 1988; Clarkson et al., 1992; Nosaka and Clarkson, 1995). These elevations are considered to provide an indirect measure of muscle damage which is characterised by an increase in muscle soreness (Clarkson and Tremblay, 1988; Clarkson et al., 1992). Excessive increases in blood CK are associated with decreased muscular function (Nosaka and Clarkson, 1994) and a reduction in athletic performance (Byrne and Eston, 2002; Twist and Eston, 2005). Thus, the assessment of circulating CK levels may contribute important information to monitoring programmes designed to evaluate the development of athletes' physical abilities.

Exercise has also been shown to elicit transient elevations in circulating hormones (Crewther et al., 2006; Smith et al., 2013), which are proposed to be necessary stimuli for training adaptation to occur (Crewther et al., 2006). Testosterone and cortisol are considered to be key endocrine markers in the training process, traditionally due to their purported involvement in muscular hypertrophy (Bhasin et al., 2001b; Viru and Viru,

2004). However, convincing evidence has challenged this direct link between testosterone and skeletal muscle hypertrophy (West et al., 2009; West et al., 2010) and more immediate effects of testosterone and cortisol have emerged as potential regulators of athletic performance (Crewther et al., 2011). For example, elevations in testosterone have been linked with behavioural changes, such as increases in workout motivation (Cook et al., 2013), which appear to be coupled with increases in self-selected training load (Cook and Beaven, 2013) and workout performance (Cook and Crewther, 2012). Conversely, exogenous cortisol has been shown to negatively influence cognitive processing in humans (Putnam et al., 2010). As such, these endocrine markers could be associated with long-term adaptive processes by influencing the short-term expression of performance across a training period, rather than through the classic genomic pathways which, ostensibly, regulate hypertrophy.

It has been suggested that dihydrotestosterone (DHT; a metabolite of testosterone) may provide a more potent stimulus for androgenic actions than testosterone partly due to a higher androgen receptor binding affinity (Bauer et al., 2000). In fact, research involving isolated muscle bundles from mice has found DHT to activate both genomic (Hamdi and Mutungi, 2011) and non-genomic (Hamdi and Mutungi, 2010) pathways to a greater extent than testosterone. As such, DHT could have an important influence on the functional capacity of skeletal muscle fibres. Furthermore, the sprint exercise-induced elevations in serum DHT in healthy men reported by Smith et al. (2013) has contributed to the generation of new scientific interest concerning the significance of this hormone in exercising muscle. However, more research is required to understand the nature of DHT responses to different exercise stimuli in elite athletes.

The primary aims of this study were to characterise the responses of selected biomarkers to maximal effort physical tests in skeleton athletes and investigate the influence of testosterone on physical performance and lean mass accrual.

5.2. Methods

5.2.1. Participants

The same athletes as those in Chapter 4 (section 4.2) participated in the current study, except two male talent squad athletes. Thus, a total of 12 British skeleton athletes

(4 female and 3 male elite squad athletes; 1 female and 4 male talent squad athletes) were involved in this study. Descriptive characteristics for each athlete group (taken at the first testing session) are presented in Table 5.1. A University of Bath Research Ethics Approval Committee for Health provided ethical approval for the physical testing and blood sampling to be conducted. A NHS Local Research Ethics Committee provided ethical approval for athletes to undergo multiple dual-energy X-ray absorptiometry (DXA) scans across one season. All athletes provided written consent prior to the collection of any data.

Table 5.1. Descriptive characteristics (mean \pm SD) for 12 skeleton athletes.

	Height (m)	Mass (kg)	Age (yr)
Male elite squad (n = 3)	1.79 \pm 0.10	84.0 \pm 6.9	26 \pm 2
Female elite squad (n = 4)	1.71 \pm 0.02	68.3 \pm 3.0	24 \pm 2
Male talent squad (n = 4)	1.73 \pm 0.04	74.1 \pm 5.5	23 \pm 1
Female talent squad (n = 1)	1.58	56.3	21

5.2.2. Study overview

As part of the ongoing athlete monitoring programme outlined in Chapter 4, fingertip capillary blood samples were collected at baseline on each testing day and then immediately before and after two physical (push-track and vertical jump) tests. Prior to the collection of the baseline samples, athletes were asked to refrain from any vigorous exercise within the preceding 36 hours. Athletes conducted a standardised warm-up immediately after the pre-test blood samples were collected on both testing days. Additionally, body composition was estimated using DXA scans at the beginning and at the end of a training season for all athletes. Typical testing schedules are provided in Table 4.2 and Table 4.3 (for the elite and talent squad athletes, respectively) and full details of the physical test protocols are provided in section 4.2.

5.2.3. Blood sampling and analysis

Capillary blood samples (500 μ l) were collected at a similar time of day across all testing sessions to account for the diurnal variation in endocrine secretion (Hayes et al., 2010). Samples were stored on crushed ice in serum collection tubes (Microvette 500; Sarstedt, Numbrecht, Germany) for approximately 30 minutes before being centrifuged at 10,000 rpm for 10 minutes (Heraeus Biofuge Pico; Kendro Laboratory Products,

Bishops Stortford, United Kingdom). Serum was immediately transferred to polypropylene Eppendorf tubes and frozen at -20° until subsequent analyses.

At the end of each training season, all samples collected across the previous training period were assayed in batch. All blood samples from the first training season (n = 371) were analysed for total testosterone and cortisol, and baseline samples (across both testing days, n = 168) were also analysed for CK. Additionally, a total of 39 samples from the first training season were analysed for free testosterone concentration. In the second training season, all samples (n = 222) were analysed for total testosterone and DHT only. Commercially available enzyme-linked immunosorbent assays (ELISAs) were used to measure serum total testosterone, cortisol, free testosterone and DHT (IBL Int., Hamburg, Germany; RE52151, RE52061, DB52181, DB52021, respectively). Samples for each participant were analysed within the same assay to control for inter-assay variance and an independent sample was run on multiple assays for further verification. Baseline samples from each testing day were analysed for CK using a commercially available kit (CK110; Randox, Crumlin, UK) and an automated RX-Daytona analyser (Randox, Crumlin, UK). As a consequence of the limited volume of serum available, paediatric cups (50µl) were used for the CK analysis. All samples were analysed in duplicate where possible (n = 230, 37, 18 and 113 samples for testosterone, cortisol, free testosterone and DHT, respectively). This was not possible for the CK analysis due to limited sample volume. Pooled intra-assay sample variation (CV) was 6.7, 3.4, 8.9 and 4.9% for testosterone, cortisol, free testosterone and DHT, respectively. Inter-assay sample variation (CV) was 6.7, 3.0 and 8.8% for testosterone, cortisol and DHT, respectively.

At all baseline blood sample time points (on both day 1 and day 2), a subjective muscle soreness assessment was also completed. This required athletes to indicate areas of soreness on a body map (Melzack, 1975) and rate the extent of perceived muscle soreness for each of these areas. This was indicated on a 100 mm visual analogue scale, in a similar way to a previous study (Hedayatpour et al., 2008) with left and right extremes marked as 'no pain' and 'unbearable pain', respectively. The level of perceived muscle soreness for each region was then scored (out of a possible 100) by measuring to the nearest mm and regional scores were summed to provide an overall measure of muscle soreness.

5.2.4. Statistical analyses

When duplicate serum samples were analysed, a mean concentration was calculated. Mean pre-test and post-test concentrations for each individual athlete were then calculated and effect sizes (\pm 90% CI) were used to assess for differences between the pre-test and post-test concentrations (from both physical tests) for male and female athletes. The changes in testosterone across push-track and jump tests (testosterone responses) were calculated by subtracting the pre-test from the post-test concentrations. At each testing session, physical performance measures were averaged across the three push-starts (V_{15} ; standard block position) and across the three countermovement jumps (max CM_{disp} - 0 kg load) for each athlete.

Pearson correlation coefficients were then used to explore the within-athlete relationships ($n = 12$) between both the baseline testosterone concentrations and testosterone responses and performance in the physical tests. Individual coefficients were then combined via Fisher transformation using an online spreadsheet (Hopkins, 2006b) to obtain an overall group correlation coefficient (\pm 90% CI). Pearson correlation coefficients (\pm 90% CI) were also used to assess the relationship between free testosterone and total testosterone concentrations. Additionally, the relationships between testosterone and DHT concentrations and responses were assessed using Pearson correlation coefficients (\pm 90% CI) for males and females, separately. Finally, the association between both lean mass accrual (change in lean mass from the beginning to the end of one training season) and several testosterone variables (all related to day 1 concentrations) in male athletes were also assessed using Pearson correlation coefficients (\pm 90% CI). These variables included:

- Total testosterone concentration and the testosterone response at baseline (first testing session) - *indicative of initial hormonal status*
- Mean testosterone (at baseline on day 1) and the mean testosterone response (to push-track testing) across all testing sessions – *indicative of the overall hormonal milieu across the training season*
- Mean testosterone (first blood sample on day 1) and the mean testosterone response (to push-track testing) relative to baseline (the differences between the first testing session and the average of subsequent testing sessions) – *indicative of the change in the hormonal milieu across the training season from baseline levels*

This analysis was not conducted in the female sub-group due to the smaller sample size. As lean mass data (estimated using DXA scans) were acquired across different seasons for the elite and talent squads, it was important to ensure blood samples were collected at the same time-points from season to season. The timings of four of the samples coincided across the two training seasons (reflecting three 8 or 9 week training blocks) and were, therefore, used to calculate the above mean testosterone concentrations and testosterone responses.

On each testing day across the first training season, means and standard deviations were calculated for baseline CK for both squads. Effect sizes (Cohen, 1988) and 90% CI were then calculated to assess for differences between day 1 and day 2 CK concentrations. The within-athlete relationships between serum CK and muscle soreness assessment scores were assessed by computing separate Pearson correlation coefficient for each of the 12 athletes. The resultant individual correlation coefficients were then combined using the method described above (Hopkins, 2006b). All effect sizes and correlation coefficients in this study were interpreted in exactly the same way as outlined in Chapter 3, section 3.2.4.

5.3. Results

5.3.1. Average hormone responses to two different physical tests

The mean pre-test and post-test hormone (testosterone, cortisol and DHT) concentrations for the push-track and vertical jump testing sessions are provided in Figure 5.1. The only substantial effects for male athletes were an increase in testosterone in response to push-track testing (effect size \pm 90% CI = 0.77 ± 0.28) and a decrease in cortisol in response to jump testing (effect size = -1.19 ± 0.58). However, for female athletes, small but substantial increases in testosterone (effect size \pm 90% CI = 0.32 ± 0.28) and DHT (effect size = 0.22 ± 0.10) were found in response to push-track testing. Additionally, a substantial decrease in cortisol (effect size \pm 90% CI = -1.70 ± 0.82) was observed in female athletes in response to push-track testing. The magnitudes of all other serum hormone responses were trivial (Figure 5.1).

A clear positive relationship ($r = 0.96$, 90% CI = 0.81 to 0.99) was observed between free and total testosterone concentrations for male athletes ($n = 7$). However, all serum

free testosterone concentrations for female athletes ($n = 20$) were found to be below the sensitivity of the assay ($0.1 \text{ pg}\cdot\text{ml}^{-1}$). Total testosterone concentrations were also positively associated with DHT at baseline for both males ($r = 0.65$, 90% CI = -0.05 to 0.92) and females ($r = 0.94$, 0.52 to 0.99). Positive relationships between the DHT responses and total testosterone responses to the countermovement jump testing for males ($r = 0.64$, 90% CI = -0.06 to 0.92) and females ($r = 0.96$, 0.65 to 1.00). Conversely, unclear relationships were observed between the DHT responses and total testosterone responses to the push-track testing for males ($r = 0.59$, 90% CI = -0.14 to 0.91) and females ($r = 0.67$, -0.34 to 0.96).

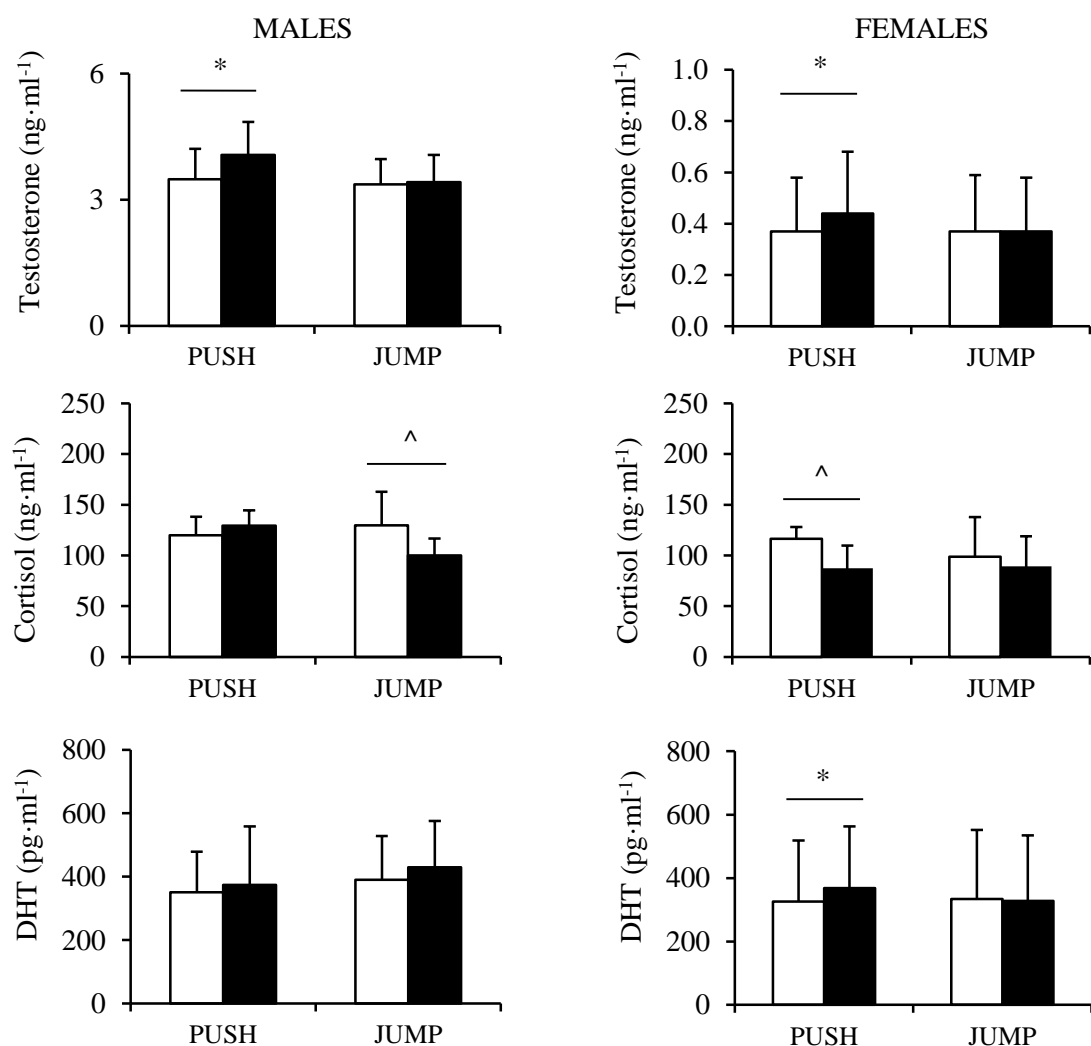


Figure 5.1. Serum hormone concentrations (mean \pm SD) before (white bars) and immediately after (black bars) two physical tests for male (left; $n = 7$) and female (right; $n = 5$) skeleton athletes. PUSH and JUMP denote push-track and countermovement jump tests, respectively. * denotes substantial increase. ^ denotes substantial decrease.

5.3.2. Correlations between serum hormones and performance

Clear positive relationships between baseline testosterone and subsequent push performance ($r = 0.28$, 90% CI = 0.02 to 0.50) were revealed by the combined within-athlete correlations (Figure 5.2). Additionally, there appears to be a weak negative relationship ($r = -0.12$, 90% CI = -0.29 to 0.06) between the testosterone response to countermovement jump testing and countermovement jump performance. Unclear relationships were observed between the testosterone response to push-track testing and push performance ($r = 0.11$, 90% CI = -0.15 to 0.36) and between baseline testosterone and countermovement jump performance ($r = -0.05$, -0.22 to 0.13).

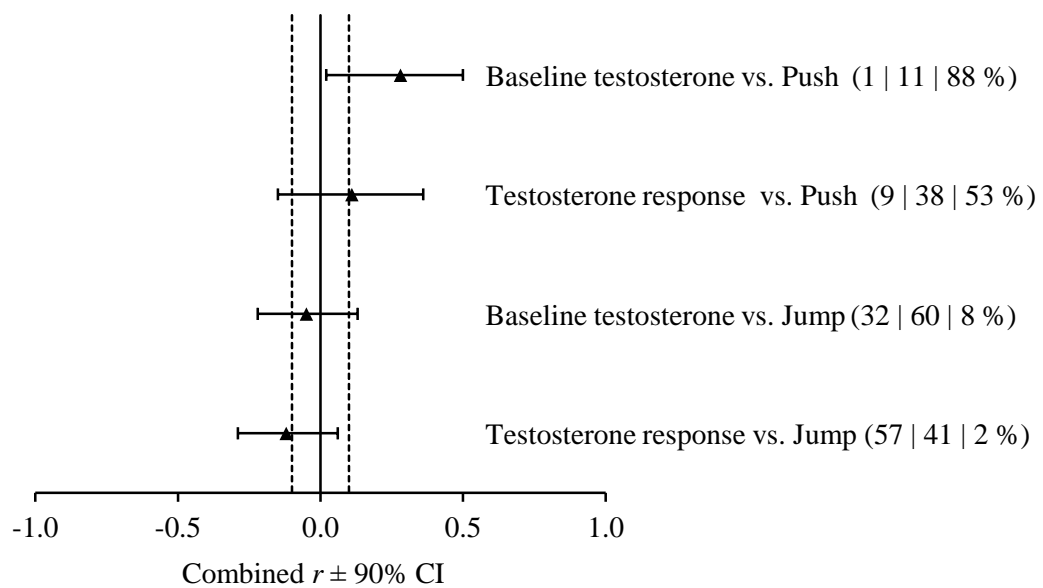


Figure 5.2. The combined correlation coefficients (r) and 90% CI for the within-athlete relationships between physical performance (push and jump) and both baseline testosterone and the testosterone response for 12 skeleton athletes. Central area ($r = 0.0 \pm 0.1$) indicates a trivial relationship. Percentages in brackets represent the likelihoods that the effect is negative | trivial | positive.

5.3.3. Serum testosterone and change in lean mass in male athletes

Total testosterone at baseline (first testing session of the season) was found to be negatively related ($r = -0.70$, 90% CI = -0.93 to -0.04) to lean mass change across the subsequent season (Figure 5.3). However, an unclear relationship was observed between the testosterone response at baseline (first testing session of the season) and gains in lean mass ($r = -0.59$, 90% CI = -0.91 to 0.12). Additionally, unclear relationships were

observed between lean mass accrual and both the mean total testosterone ($r = -0.33$, 90% CI = -0.82 to 0.55) and mean testosterone response ($r = -0.38$, -0.84 to 0.40) to push-track testing (calculated across all time-points within one training season). However, clear positive relationships between lean mass change and both the mean total testosterone relative to baseline (i.e. the difference between the first testing session and the average of subsequent testing sessions; $r = 0.81$, 90% CI = 0.30 to 0.96) and the mean testosterone response (to push-track testing; $r = 0.66$, -0.03 to 0.92) relative to baseline were observed (Figure 5.3).

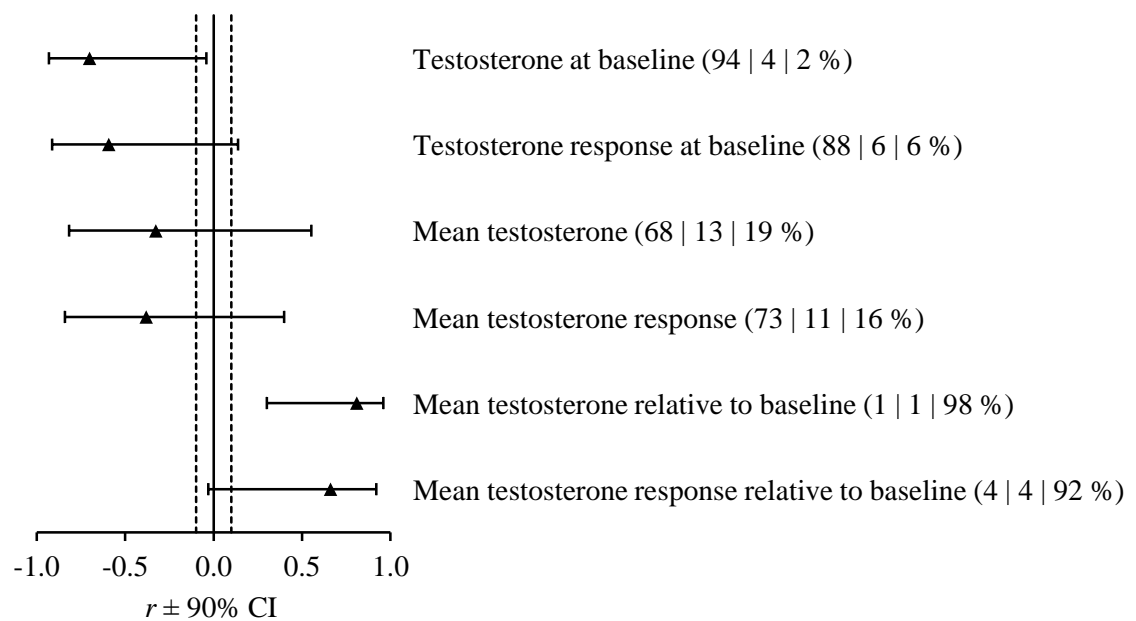


Figure 5.3. The correlation coefficients (r) and 90% CI for the relationships between lean mass change across a training season and selected total testosterone measures in seven male skeleton athletes. Central area ($r = 0.0 \pm 0.1$) indicates a trivial relationship. Percentages in brackets represent the likelihoods that the effect is negative | trivial | positive.

5.3.4. Serum creatine kinase and muscle soreness

Mean baseline serum CK (\pm SD) concentrations on the two consecutive testing days for the elite squad skeleton athletes are illustrated in Figure 5.4. Substantial increases in CK between day 1 and day 2 were observed at every time point for elite athletes (effect sizes \pm CI ranged from 0.45 ± 0.39 to 2.14 ± 0.77 ; Figure 5.4).

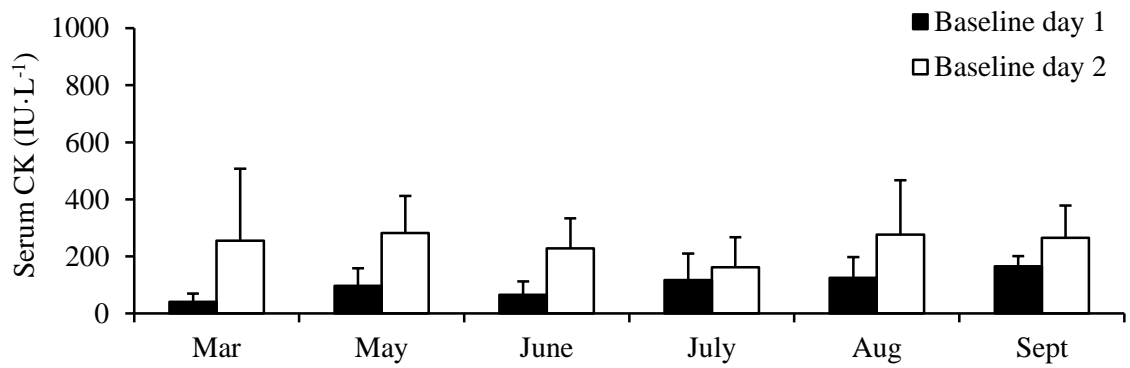


Figure 5.4. Baseline serum creatine kinase (CK) concentrations (mean \pm SD) on two consecutive testing days across a season for elite squad skeleton athletes ($n = 7$).

A similar effect was found for the talent squad athletes (effect sizes \pm CI ranged from 1.40 ± 1.00 to 4.81 ± 3.60 ; Figure 5.5) except at the May testing session, where a high baseline CK on day 1 (481 ± 241 IU·L⁻¹, mean \pm SD) and a trivial CK increase (effect size = 0.12 ± 0.22) from baseline day 1 to baseline day 2 were observed.

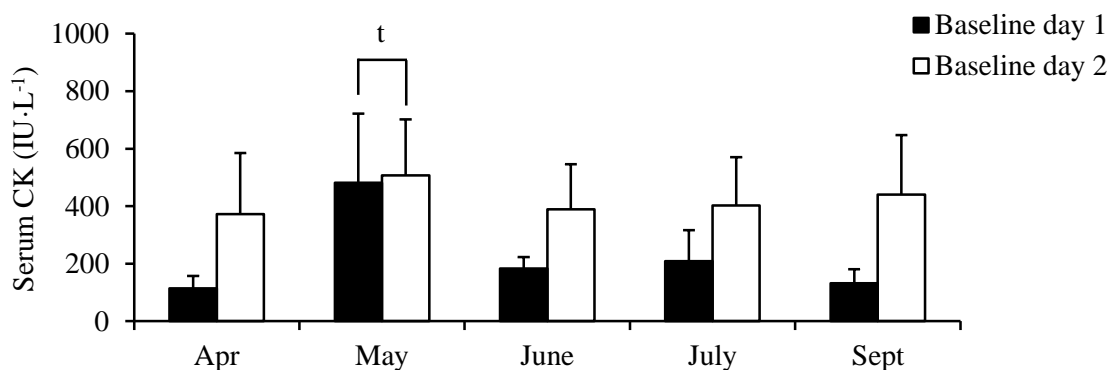


Figure 5.5. Baseline serum creatine kinase (CK) concentrations (mean \pm SD) on two consecutive testing days across a season for talent squad skeleton athletes ($n = 5$). 't' denotes a trivial increase in CK from day 1 to day 2.

The extent of muscle soreness perceived by elite squad athletes on the consecutive testing days across the training season are illustrated in Figure 5.6. Substantial increases in muscle soreness between the first and second testing day were observed at most time points (effect sizes \pm CI ranged from 0.27 ± 0.35 to 1.06 ± 1.00) except in September where a trivial increase was observed (effect size \pm CI was 0.03 ± 0.10).

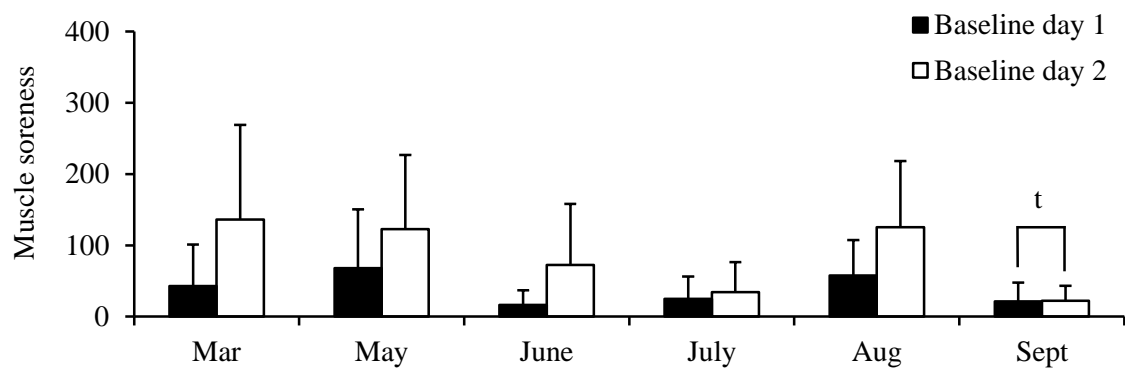


Figure 5.6. Muscle soreness assessment scores (mean \pm SD) reported on two consecutive testing days across a season for elite squad skeleton athletes ($n = 7$). ‘t’ denotes a trivial increase in muscle soreness from day 1 to day 2.

In a similar way to the serum CK responses, muscle soreness for the talent squad athletes was elevated on the second testing day at every time point (effect sizes \pm CI ranged from 0.24 ± 0.30 to 2.54 ± 1.70 ; Figure 5.7) except at the May testing session where an unclear increase in perceived muscle soreness was observed (effect size \pm CI was 0.32 ± 0.83).

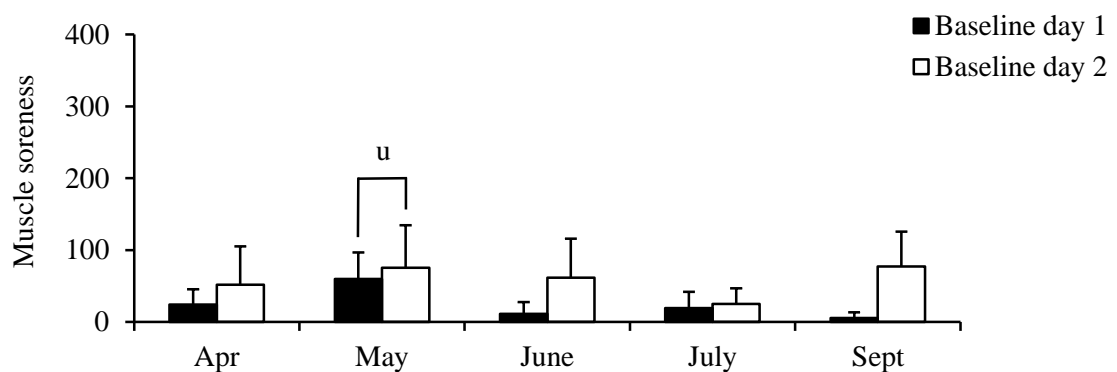


Figure 5.7. Muscle soreness assessment scores (mean \pm SD) reported on two consecutive testing days across a season for talent squad skeleton athletes ($n = 5$). ‘u’ denotes an unclear increase in muscle soreness from day 1 to day 2.

Muscle soreness assessment scores were positively associated (r ranged from 0.35 to 0.71) with baseline CK for eight of the 12 athletes (Figure 5.8). When these correlation coefficients were combined, an overall positive within-athlete relationship was revealed (combined $r = 0.50$, 90% CI = 0.38 to 0.64) between serum CK and muscle soreness.

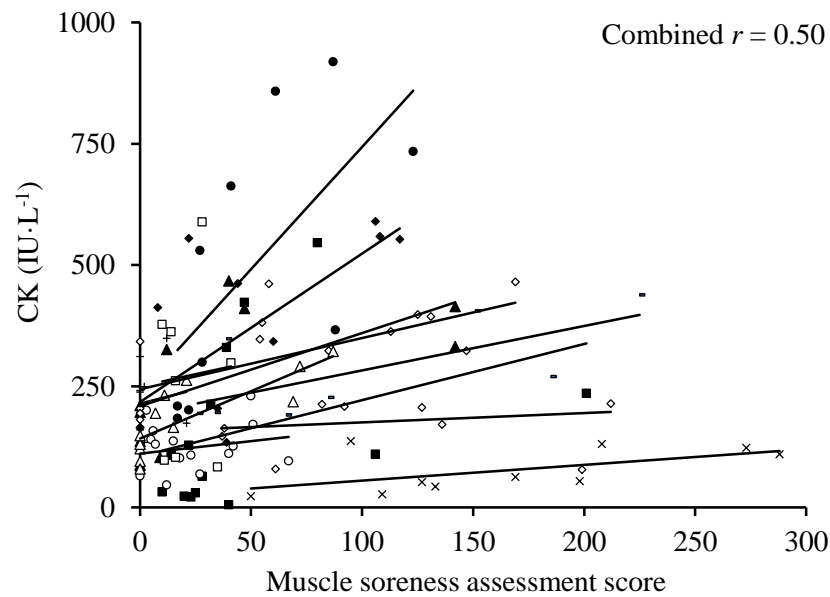


Figure 5.8. Within-athlete relationships ($n = 12$) between muscle soreness assessment scores and serum creatine kinase (CK) concentrations across all testing sessions in the first training season. Each symbol represents an individual athlete and linear trendlines represent within-athlete correlations.

5.4. Discussion

The primary aim of this study was to characterise the biochemical responses to two physical exercises and investigate the influence of testosterone on performance and long-term training gains. A key finding was that push-track testing seemed to provide a more potent stimulus to evoke an increase in circulating testosterone concentration. Additionally, baseline testosterone appeared to influence the expression of push-start performance and maintaining or increasing testosterone across a training season appeared to be important for the accumulation of lean mass.

The nature of the current study allowed unique longitudinal data to be collected in a truly elite training environment and thus, the role of biochemical markers in the training process could be further explored in well-trained skeleton athletes. Within-athlete variability in baseline testosterone was found to be related to push-track performance ($r = 0.28$, 90% CI = 0.02 to 0.50) providing some support to the short-term effects of testosterone (Crewther et al., 2011). As such, baseline testosterone appears to reflect the so-called ‘readiness to perform’ at the push-track and routine monitoring of testosterone in athletes may be warranted, as previously suggested (Cardinale and Stone, 2006).

Additionally, this points towards (but cannot confirm) the potential to enhance performance through testosterone-promoting interventions. In fact, Cook and Crewther (2012) have previously used short video clips to elicit increases in salivary free testosterone and found subsequent workout performance to be improved.

As lean mass was shown to be positively associated with skeleton start performance in Chapter 4, a biochemical marker which reflects the potential for lean mass accrual could provide valuable insight to skeleton start training. If the short-term effects on athletic performance do exist, testosterone may conceivably be implicated in the long-term adaptive training processes through the regulation of workout performance, rather than through a direct influence on the anabolic pathways involved in skeletal muscle hypertrophy. In this study, lean mass change across a season was not related to either the mean basal testosterone or the mean testosterone response recorded across a training season (Figure 5.3). Thus, the absolute concentration of testosterone that the muscle is exposed to (as indicated by mean testosterone concentration) does not seem to relate to the lean mass gains exhibited across a training period. These findings are potentially surprising given the associations between average testosterone across a resistance training programme and strength adaptation, which have been documented on numerous occasions (Raastad et al., 2001; Ahtiainen et al., 2003; Crewther et al., 2009; Crewther et al., 2012a; Cook et al., 2013). However, this finding is in support of a previous study (West and Phillips, 2012) which reported free testosterone concentration (at the mid-point of a 12 week resistance training block) to be unrelated to gains in lean body mass in a large cohort of young men. The findings that testosterone does not directly enhance muscle protein synthesis (West et al., 2009) or training-induced hypertrophy (West et al., 2010) of the elbow flexors provides a convincing explanation for this finding. Furthermore, Mitchell et al. (2013) have suggested that intramuscular factors (such as phosphorylation of p70S6k) explain a much greater portion of the variance in resistance exercise-induced muscle hypertrophy than systemic factors such as elevated circulating testosterone.

Additionally, baseline testosterone at the start of the season did not seem to indicate potential for lean mass accrual across the subsequent training season in the current study. This is in line with a previous study which found individual changes in several strength measures across a six week resistance training programme to be unrelated to

baseline testosterone ($r = -0.11 \pm 0.49$) in club-level 7s rugby union players (Crewther et al., 2013). In fact, the male athletes with the greatest increases in lean mass in the current study exhibited the lowest baseline testosterone concentration and the smallest testosterone response at the start of the training season, opposing previous suggestions that baseline testosterone is capable of predicting subsequent training-induced muscle hypertrophy (Ahtiainen et al., 2003). Interestingly, however, the mean testosterone and testosterone response relative to baseline (i.e. the difference between the first testing session and the average of subsequent testing sessions) were both found to be positively related to lean mass change across the season ($r = 0.81$ and 0.66 , respectively). Thus, longitudinal changes in testosterone appear to be more important markers of ‘adaptation potential’ than discrete testosterone concentrations. Indeed, previous studies have also associated longitudinal increases in basal testosterone with superior adaptation to training (Häkkinen et al., 1985c; Häkkinen et al., 1988; Häkkinen and Pakarinen, 1991; Raastad et al., 2001; Ahtiainen et al., 2003). Overall, these findings point towards the possibility that maintaining or increasing circulating testosterone across a training season reflects a favourable hormonal milieu for hypertrophy.

As the link between testosterone and hypertrophy does not appear to be a direct effect of testosterone on muscle protein synthesis (West et al., 2009), alternative mechanisms have been explored. The most likely pathways appear to be related to the influences of testosterone on behavioural factors such as aggression (Book et al., 2001) and motivation (McCall and Singer, 2012), which have been suggested to contribute to the short-term effects of testosterone on athletic performance (Crewther et al., 2011). In fact, elevations in salivary testosterone have been associated with higher self-selected training load (Cook and Beaven, 2013) and enhanced work out performance (Cook and Crewther, 2012; Cook and Beaven, 2013) potentially through the regulation of training motivation (Cook et al., 2013). This effect could be practically significant across a training season, as a larger overall volume of training may be conducted and thus, a potentially greater stimulus for adaptive responses could be induced. Further research is required to explore the factors which contribute to these longitudinal changes in testosterone and to identify potential interventions which elicit increases in (or aid the maintenance of) circulating testosterone across a training season.

Overall, the longitudinal analysis of testosterone seems to be able to provide some additional insight to the training process, beyond that of the conventional physical tests. However, as biochemical monitoring should provide coaches with data that can be used to make objective and immediate decisions regarding the training process, the retrospective and time-consuming nature of these analyses may currently limit their utility in the applied setting. The development of more time-efficient, field-based analysis methods to provide valid and reliable information to coaches and sports scientists more immediately, is perhaps required for this testing to inform training practice in the real-world. Currently, it is possible to conduct this analysis on the same day as the testing sessions, which could conceivably provide some level of insight into an athlete's underlying physiological status. However, this is not only more expensive than the analysis methods used in the current study (because microtiter plates are likely to be incomplete, for example) but may also introduce further variability if samples from one athlete are analysed across different assays.

In recent years, more emphasis has been placed on unbound (free) testosterone, rather than the total systemic concentration, as this is thought to reflect the 'biologically active' fraction of this hormone. Consequently, non-invasive salivary analysis (measuring free testosterone only) is sometimes the preferred approach in this setting (Beaven et al., 2008b; Crewther et al., 2012b; Cook and Beaven, 2013). However, the free testosterone concentration in all 20 female samples was found to be below the limit of detection ($0.1 \text{ pg} \cdot \text{ml}^{-1}$) in this study. Thus, it was not possible to measure free testosterone in any female skeleton athlete using this method. Additionally, Dunn et al. (1981) presented evidence to suggest that the abundant albumin-bound portion of testosterone (~50% of total testosterone) may be able to enter cells and should perhaps be considered somewhat bioavailable (Manni et al., 1985). This albumin-bound fraction has also been linked with the non-genomic actions of this hormone (Estrada et al., 2000; Estrada et al., 2003), the functional significance of which is now emerging (Crewther et al., 2011). Thus, collectively this evidence distinguishes total testosterone as a more appropriate biomarker than free testosterone, at least in the current study.

Serum testosterone concentration was found to be elevated following the push-track testing session in both male (effect size \pm 90% CI = 0.77 ± 0.28) and female (effect size = 0.32 ± 0.28) athletes, however no change in testosterone was observed in

response to the vertical jump testing (Figure 5.1). Stokes et al. (2013) illustrated that, although elevations in testosterone can occur in response to different types of exercise (resistance, sprint and endurance) stimuli, the characteristics of the sessions influence the magnitude of the response. Hypertrophy-based sessions (characterised by high volume, short rest intervals and typically involve large muscle mass) have been associated with the greatest testosterone responses in saliva (Crewther et al., 2008) and serum (Smilios et al., 2014). Conversely, certain resistance training protocols, particularly those with emphasis on maximum strength and power development (characterised by a low number of repetitions, small volume of work and long rest periods), have been found to elicit little or no acute testosterone response, when conducted on a one-off occasion (Linnamo et al., 2005; Crewther et al., 2008; McCaulley et al., 2009). These observed discrepancies could somewhat explain the differences in the acute testosterone response between sessions in this study, as the push-track testing may be considered to involve more muscle groups and perhaps a greater volume of exercise than the vertical jump testing. Although previous literature has observed an association between testosterone and jump performance (Bosco et al., 1996a; Bosco et al., 1996b; Cardinale and Stone, 2006), no relationship was observed between testosterone and countermovement jump performance in this study (Figure 5.2). Given the relationships between testosterone and push performance observed in this study, it could be that the magnitude of the testosterone response is indicative of the influence of testosterone on that performance.

Elevations in cortisol have also been documented in response to hypertrophy-based workouts (Häkkinen and Pakarinen, 1993; Smilios et al., 2003; Crewther et al., 2008; McCaulley et al., 2009), somewhat challenging the long-standing views that testosterone and cortisol have distinct and opposing actions (McGrath and Goldspink, 1982). However, no increases in cortisol were observed in response to either physical test in the current study (Figure 5.1). The metabolic demands of the different testing sessions are considered to influence the cortisol response. For example, Stokes et al. (2013) reported no change in cortisol in response to a bout of resistance training. However, the same study found cortisol to be elevated following an all-out 30 second cycle sprint. It may, therefore, be surprising that no elevation in cortisol was observed in this study in response to the push-track tests, which are largely sprint-based. Additionally, the reasons behind the observed substantial decreases in cortisol for

female athletes in response to push-track testing and for male athletes in response to the jump testing are unclear. Previous research has reported an acute reduction in circulating cortisol in response to certain heavy resistance training sessions (Smilios et al., 2003; Beaven et al., 2008b; Crewther et al., 2008). However, no sex differences in the cortisol response have previously been reported (Häkkinen and Pakarinen, 1995; Pullinen et al., 2002; McGuigan et al., 2004). The known large inter-individual variation in hormonal responses (Stokes, 2003), along with the small sample sizes in the current study may be accountable for the seeming lack of agreement with previous literature. Alternatively, as circulating cortisol concentrations are known to progressively decrease throughout the day in men and women (Aubets and Segura, 1995), the observed 'reduction' in cortisol in female athletes may simply reflect that circadian variation. It could then be interpreted that the maintenance of circulating cortisol observed in male athletes across the push-track tests may actually reflect a hormonal response.

The role of testosterone as the primary androgen in training adaptation has come under further scrutiny and a metabolite of testosterone (DHT) has been shown to have a higher androgen receptor affinity compared with testosterone (Bauer et al., 2000). Moreover, isolated animal muscle models have suggested that DHT may provide a more potent stimulus than testosterone for certain non-genomic (Hamdi and Mutungi, 2010) and genomic (Hamdi and Mutungi, 2011) pathways, such as the expression of force production in type II muscle fibres. This has generated new scientific interest surrounding the significance of this hormone in exercise performance. To the author's knowledge, there has been only one previous study which has documented blood DHT responses to exercise in humans (Smith et al., 2013). In this previous study, elevations in DHT in response to sprint cycle exercise were found to be short-lived (returning to baseline levels within an hour) and followed a similar time course to testosterone. In the current study, there was evidence for an increase in DHT in response to the push-track sessions in female athletes only (effect size \pm 90% CI = 0.22 ± 0.10). It is unclear as to why DHT concentration in male athletes was not elevated in response to the same sessions as testosterone, as common pathways are considered to drive these responses. In fact, positive associations between these hormonal responses were observed in this study (section 5.3.1) and to a bout of sprint cycle exercise previously (Smith et al., 2013). A potential explanation could be related to the large inter-individual variation in DHT responses observed in this study (Figure 5.1). Alternatively, as DHT is considered

an autocrine hormone (acts locally within the tissue it is formed), circulating concentrations are typically lower than other androgens (Luu-The and Labrie, 2010) and may not accurately reflect the intramuscular bioconversion of testosterone to DHT in response to exercise. Thus, the potentially important actions of these hormones on skeletal muscle function may not be detectable through the analysis of systemic concentrations. Further work is clearly required to understand the physiological significance of the intramuscular DHT responses to exercise stimuli.

The appearance of intramuscular proteins (such as CK) in the blood is considered to provide indirect evidence of skeletal muscle fibre damage (Clarkson and Hubal, 2002). As such, the first testing day in the current study appears to have induced muscle damage to a certain extent, with an average increase in serum CK of 145% (across 24 hours from first to second testing day). Of concern when attempting to monitor athletes is a potential loss of muscle function which can accompany exercise-induced muscle damage (Byrne et al., 2004) and could potentially be detrimental to performance on the subsequent day(s). However, much larger CK increases than those observed here have been associated with reductions in performance on the following day. For example, Byrne and Eston (2002) found blood CK responses of ~600% (baseline to 24 hours post-exercise) to be associated with ~10% decreases in countermovement jump height in non-resistance trained individuals. The level of muscle damage observed in the current study may not, therefore, be expected to adversely affect the skeleton athletes' performances during the second testing day. In fact, very high serum CK concentrations (exceeding $1000 \text{ IU}\cdot\text{L}^{-1}$) have been shown to fall within the normal range for training athletes (Mougios, 2007). Consequently, the serum CK responses observed here (baseline day 2 mean concentrations were 240 and $413 \text{ IU}\cdot\text{L}^{-1}$ for the elite and talent squad, respectively) do not appear to be atypical for this population and may not be indicative of an excessive level of muscle damage. To the author's knowledge, however, no studies to date have actually investigated the performance implications of such modest levels of muscle damage in elite power athletes, such as the population involved in the current study.

There is some evidence from animal studies which points towards the existence of sex differences in CK responses (Amelink and Bar, 1986), with some suggestions that males are more susceptible to muscle damage than females, potentially due to a

protective effect of oestrogen (Kendall and Eston, 2002). In contrast, the findings surrounding any sex differences in muscle damage resistance are less clear in humans (Clarkson and Sayers, 1999). Indeed, in the current study sex differences between CK responses to the first testing day were trivial (effect size = 0.19) and certainly within the normal inter-individual variation. Kendall and Eston (2002) have previously suggested that regularly ingesting oestrogen (in the form of the oral contraceptive pill) may have a protective effect on muscle damage. Although this information was not available in the current study, such an effect may warrant consideration when assessing the longitudinal changes in CK response in female athletes.

Increasing the volume of eccentric exercise has been associated with greater serum CK responses and heightened muscle soreness (Clarkson and Tremblay, 1988). However, some correlational studies have been unable to detect a relationship between the CK response and muscular soreness at a group level (Rodenburg et al., 1993; Nosaka et al., 2002). This may be partly attributable to the high inter-individual variation in the CK response to the same exercise stimulus (Nosaka and Clarkson, 1996) and/or the subjective nature of muscle soreness reporting (Nosaka et al., 2002). Such variation is illustrated by the different gradients of the trendlines for the relationships between muscle soreness and serum CK in Figure 5.8, highlighting the importance to investigate longitudinal changes in muscle damage and/or soreness at a single subject level. In the current study, clear positive associations were observed between muscle soreness assessment scores and serum CK concentrations (combined $r \pm 90\% \text{ CI} = 0.50$). Thus, the longitudinal tracking of perceived muscle soreness appears to reflect this microtrauma or disruption to skeletal muscle cells, and if attempting to obtain insight regarding the internal stress invoked by a maximal physical test, the simple muscle soreness assessment used in this study appears to offer similar information to the serum CK analysis. However, the nature of the muscle soreness assessment (i.e. non-invasive, time efficient and cost-effective) likely distinguishes this as a more favourable and practical method, than the fingertip capillary blood sampling.

Interestingly, the most substantial increase in serum CK and muscle soreness for the elite squad was observed in the June testing (Figure 5.4 and Figure 5.6, respectively), coinciding with the end of a four week period of lighter training (Figure 4.1). It is well documented that performing one bout of muscle damaging exercise (typically

comprising high forces during muscle lengthening) can elicit an adaptive response, resulting in a resistance to subsequent damage of the same nature (Clarkson and Hubal, 2002). This so-called 'repeated bout effect' has been shown to protect skeletal muscle from such damage for several months depending on the extent of muscle damage induced initially (McHugh et al., 1999). At the June time point, essentially the same exercise stimulus (identical number of repetitions at maximum exertion) seemingly induced more extensive muscle damage than at the other time points. This may suggest that the training conducted across the four week period before the June testing did not provide the same protective effect as that preceding the other testing sessions, and thus, a greater level of muscular trauma was experienced.

Further noteworthy observations were a higher concentration of baseline CK ($481.0 \pm 240.9 \text{ IU}\cdot\text{L}^{-1}$; mean \pm SD) for the talent squad at the May testing session and a subsequently attenuated CK response to the first testing day ($26.3 \pm 217.6 \text{ IU}\cdot\text{L}^{-1}$; mean \pm SD). This was concomitant with the greatest baseline muscle soreness assessment scores reported on the first testing day across all testing sessions (Figure 5.7). Although it was unknown to the researchers at the time, talent squad athletes underwent a separate set of physical tests (the final testing session of a talent identification programme involving sprint- and power-based tests) 48 hours prior to the May testing session. Thus, the first bout of testing does appear to have induced a certain level of skeletal muscle damage as both serum CK and perceived muscle soreness were elevated at baseline on day 1. Although it is not possible to isolate the exact influence of this muscular trauma on muscular performance, it is perhaps noteworthy that (despite undergoing an intensive 4 week training block) only two out of six talent squad athletes achieved faster push-start velocities in May, compared with the previous testing session. Thus, it is conceivable (but not quantifiable) that physical performance during this testing session was negatively affected.

A blunted CK response has been reported elsewhere when initial blood CK concentrations are elevated and this is believed to indicate an accelerated clearance rate by the lymphatic system (Nosaka and Clarkson, 1994). This illustrates an important consideration for this type of biochemical monitoring, as circulating muscle proteins reflect both what is released from the muscle, as well as the concentration which is cleared from the blood. Separating these two factors is not possible through

conventional blood analysis and this has important implications for the interpretation of biochemical markers, particularly when basal concentrations are not consistent across time.

5.4.1. Conclusion

This study presents unique longitudinal data regarding the concentrations of selected biomarkers across a training season in skeleton athletes, and discusses the potential influence of testosterone on physical performance and adaptive responses to training. The findings of this study provided some support for the short-term effects of testosterone on the neuromuscular system, which appear to influence the expression of push-track performance in skeleton athletes. Additionally, increasing circulating testosterone and the responsiveness of testosterone across a training season was found to be potentially important for lean mass accrual. Discrete analyses of absolute hormone concentrations seem unable to detect these potentially important changes in baseline testosterone. As such, the longitudinal analysis of testosterone in athletes appears to be necessary to obtain this kind of insight. Conversely, the serum DHT responses to the physical tests observed in this study did not provide any clarity surrounding the functional significance of this hormone, perhaps due to the observed variability in these responses and/or the autocrine action of this hormone. Although a seemingly sensitive measure of training status, the observed serum CK responses to a battery of tests in this study were not indicative of excessive levels of muscle damage. Additionally, it appears that similar information can be obtained using a simple subjective muscle soreness assessment and the exploration of less invasive and more immediate assessments than the capillary blood analysis is encouraged in this setting.

CHAPTER 6: EVALUATING LONGITUDINAL CHANGES IN BODY COMPOSITION AND THE INFLUENCE OF THESE CHANGES ON PHYSICAL PERFORMANCE

6.1. Introduction

Several body composition measures emerged as important determinants of skeleton start performance in Chapter 4. For example, both total body lean mass and leg lean mass were positively associated with sled velocity, whereas fat mass appeared to be detrimental to performance. Thus, body composition appears to be an important physical characteristic to monitor in this population. The use of dual-energy X-ray absorptiometry (DXA) scans to characterise physique (Sutton et al., 2009a; Sutton et al., 2009b) and body composition changes (Santos et al., 2010; Harley et al., 2011; Silva et al., 2012; Milsom et al., 2014) amongst athletic populations is ever-increasing. However, the reliability of DXA measurements in applied sport settings is sometimes overlooked and the inherent measurement errors are seldom considered when evaluating body composition changes.

Biological variation (including differences in food or fluid intake and the short-term effects of exercise) is known to inflate the measurement errors (Pietrobelli et al., 1998; Nana et al., 2012, 2013), which in turn may influence the ability of DXA to detect ‘true’ body composition changes across time (Nana et al., 2014). Thus, a meticulous scanning protocol has been outlined (Nana et al., 2012, 2013) in order to minimise the errors in DXA body composition estimates. This requires athletes to be fasted, rested, euhydrated and carefully positioned on the scanning bed using custom-made blocks. However, this level of control is not always achieved in the applied setting partly due to the complexity of training programmes and inflexibility of dietary regimes. Thus, it is currently unknown whether ‘true’ body composition changes in response to training can be detected above the inflated measurement errors in athletic populations.

Strength and conditioning programmes can result in considerable body composition changes (Burke et al., 1986; Gabbett, 2005; Legaz and Eston, 2005) which may contribute to explosive performance by influencing the crucial power-to-body mass ratio that underlies many athletic movements (Cronin and Hansen, 2005). Indeed, decreases in lower limb skinfold measurements have previously been associated with

improvements in sprint performance (Legaz and Eston, 2005). However, it is yet to be established whether DXA-estimated body composition changes are associated with changes in physical performance.

Thus, this study aimed to firstly establish the reliability of DXA in the applied setting, by quantifying the measurement errors when athletes from diverse sports are scanned using a realistically controlled DXA protocol. The second aim was to use these measurement errors to evaluate body composition changes exhibited by skeleton athletes across a training and competition season. Further, in order to better understand the performance implications of these changes, the associations between changes in body composition and lower limb strength and power measures were investigated.

6.2. Methods

6.2.1. Participants

Forty-eight athletes across four sports (12 skeleton, 8 rugby union, 14 swimming and 14 athletics sports men and women) participated in this study (Table 6.1). Skeleton athletes included in this study were the same as those in Chapter 5. The 8 rugby union players were all professional forward players and were competing in the top tier of rugby union in England. Athletes comprising the swimming and athletics sub-groups were competitive at an international or university level. A NHS Local Research Ethics Committee and a University of Bath Research Ethics Approval Committee for Health provided ethical approval for this study (DXA scans and physical tests, respectively) to be conducted and each athlete provided informed consent prior to participating.

6.2.2. DXA and physical test protocols

All athletes underwent two whole-body DXA scans typically within 48 hours (4-6 days for rugby players). The DXA scans for skeleton athletes were collected and analysed as part of this project, however body composition data for all athletes from other sports (rugby, athletics and swimming) were collected and analysed between 2008 and 2011 by a trained technician.

Table 6.1. Subject characteristics (mean \pm SD) at baseline (first DXA scan).

	Skeleton		Rugby	Athletics		Swimming	
	7 male	5 female	8 male	7 male	7 female	7 male	7 female
Age (yr)	25 \pm 1	24 \pm 1	28 \pm 4	21 \pm 2	20 \pm 2	21 \pm 3	20 \pm 1
Height (m)	1.76 \pm 0.07	1.68 \pm 0.05	1.86 \pm 0.08	1.83 \pm 0.04	1.68 \pm 0.05	1.87 \pm 0.05	1.71 \pm 0.06
Body mass (kg)	77.5 \pm 7.5	65.6 \pm 6.5	112.7 \pm 9.0	76.4 \pm 6.1	59.9 \pm 6.3	80.2 \pm 4.5	66.2 \pm 5.4
Lean mass (kg)	64.9 \pm 6.7	50.7 \pm 5.5	85.0 \pm 7.2	66.8 \pm 5.1	45.2 \pm 4.3	68.6 \pm 3.8	48.6 \pm 4.4
Fat mass (kg)	9.5 \pm 1.5	11.9 \pm 1.6	23.1 \pm 5.1	6.3 \pm 2.0	12.0 \pm 3.5	8.4 \pm 1.4	15.3 \pm 2.6
Body fat %	12.2 \pm 1.9	18.2 \pm 1.9	20.5 \pm 3.8	8.2 \pm 2.4	19.8 \pm 4.5	10.5 \pm 1.5	23.0 \pm 3.4

Body composition was estimated using a DXA system (Hologic Discovery W, Bedford, MA; QDR software version 12.4.2) by differentiating the fat, bone and non-bone, non-fat (lean) masses. This procedure is fully outlined in Chapter 4. All scans were undertaken at a similar time of day (typically within 90 minutes of each other) to control for the natural diurnal variation. Athletes were asked to wear light clothing (males: cycling shorts; females: cycling shorts and unwired sports bra) and remove all metal objects before each scan. It was not possible to control the exact food and fluid consumption in the rugby, athletics or swimming sub-groups in the immediate pre-scan period. More controls (over scheduling and food or drink consumption) were possible for the skeleton athletes' scans, as outlined in section 4.2.2. Immediately after the scan, operational procedures were followed by a trained technician to manually place boundaries around discrete anatomical regions (left arm, right arm, trunk, left leg, right leg and head) within the software, before the system calculated regional masses and composition.

The initial scans were conducted at the beginning of the training season for skeleton athletes, who underwent two (talent squad) or three (elite squad) further DXA scans each at the end of a training or competition block (as stated in Chapter 4). For the elite squad, this represented two training blocks (each 12 weeks) and the competition season (approximately 24 weeks). The emphasis of the first training block (block 1) was hypertrophy, whereas the second training block (block 2) involved higher velocity, sprint-based exercises (Figure 4.1). The season for the talent squad skeleton athletes consisted of one 24-week training block and the competition season (approximately 17 weeks). Within one week of each DXA scan, all skeleton athletes completed countermovement jump and leg press testing. The protocols have been fully outlined previously (section 4.2.2). In Chapter 4, maximum CM_{disp} under the 0 kg load and Keiser leg press FP_{max} were found to significantly contribute to the prediction of sled velocity at the 15 m mark (V_{15}) and so were used in the current study as measures of vertical jump and leg press performance, respectively.

6.2.3. Statistical analysis

Means and standard deviations for body composition measures were calculated for each athlete sub-group. These included total mass, lean mass and fat mass for the whole body, as well as the trunk, leg and arm regions. Data from repeated scans were used to

calculate typical error of the measurements (TEMs; in grams and %) and intraclass correlation coefficients (ICCs) for all body composition measures using a published spreadsheet (Hopkins, 2000b). To express the typical errors in percent units, each of these measurements were firstly log transformed before analysis and back transformed after analysis, as recommended by Hopkins (2000a).

Typical error of the measurements were derived for the whole cohort and for each sub-group of athletes (each sport separated by sex; $n = 7$) and uncertainty in the estimates were expressed as 90% confidence limits (CL). According to Hopkins (2000a), the TEM should be multiplied by a factor of 1.5 to 2 before interpreting longitudinal changes. Thus, TEMs were doubled to provide a conservative ‘TEM threshold’ above which body composition changes were considered ‘true’. Pearson correlation coefficients ($\pm 90\%$ CI) were used to assess the relationship between the mean (for each sub-group) fat masses and the fat mass TEMs of the associated body regions.

For the follow-up DXA scans (skeleton athletes only), percentage changes (from baseline and between time points) in four body composition measures (total body mass, lean mass, fat mass, leg lean mass) were calculated at each time point. The percentage changes in total lean mass, leg lean mass and physical test scores across all testing blocks were then pooled and Pearson correlation coefficients ($\pm 90\%$ CI) were used to assess the relationships between the percentage changes in body composition and the physical test scores. Correlation coefficients were interpreted in exactly the same way as in previous chapters (see section 3.2.4 in Chapter 3 for full details).

6.3. Results

6.3.1. The reliability of DXA measurements

Typical errors and ICCs associated with the repeated DXA measurements are provided in Table 6.2. Regional TEMs (%) were found to be larger than those associated with whole body measures. Additionally, fat mass TEMs (%) were consistently larger than the total mass and lean mass TEMs of the same body region.

Table 6.2. Reliability statistics for DXA estimated body composition measures (n = 48).

		Typical error of the measurement			ICC
		(g)	(%)	(CL)	
Whole body	Total mass	506	0.6	1.2	1.00
	Lean mass	549	0.9	1.2	1.00
	Fat mass	359	3.9	1.2	0.99
Legs	Total mass	313	1.0	1.2	1.00
	Lean mass	290	1.2	1.2	1.00
	Fat mass	185	4.5	1.2	0.99
Arms	Total mass	143	1.6	1.2	1.00
	Lean mass	156	2.3	1.2	1.00
	Fat mass	63	7.7	1.2	1.00
Trunk	Total mass	496	1.4	1.2	1.00
	Lean mass	510	1.8	1.2	1.00
	Fat mass	298	8.0	1.2	0.98

CL = 90% confidence limits in \times/\div form (typical errors in g and % can be multiplied or divided by this factor to obtain exact upper and lower CL, respectively)

Total fat mass errors varied across sub-groups and were typically greater in the leaner athlete sub-groups. The relationships between absolute fat mass and absolute fat mass TEMs are illustrated in Figure 6.1. Trunk fat mass TEMs were typically higher for the athlete sub-groups with lower trunk fat masses ($r = -0.78$, 90% CI = -0.95 to -0.22). Additionally, a positive relationships was observed between total fat mass and total fat mass TEMs ($r = -0.62$, 90% CI = -0.81 to -0.14). Unclear relationships were found between arm fat mass and arm fat mass TEMs ($r = 0.08$, 90% CI = -0.63 to 0.72), as well as between leg fat mass and leg fat mass TEMs ($r = 0.53$, -0.23 to 0.89).

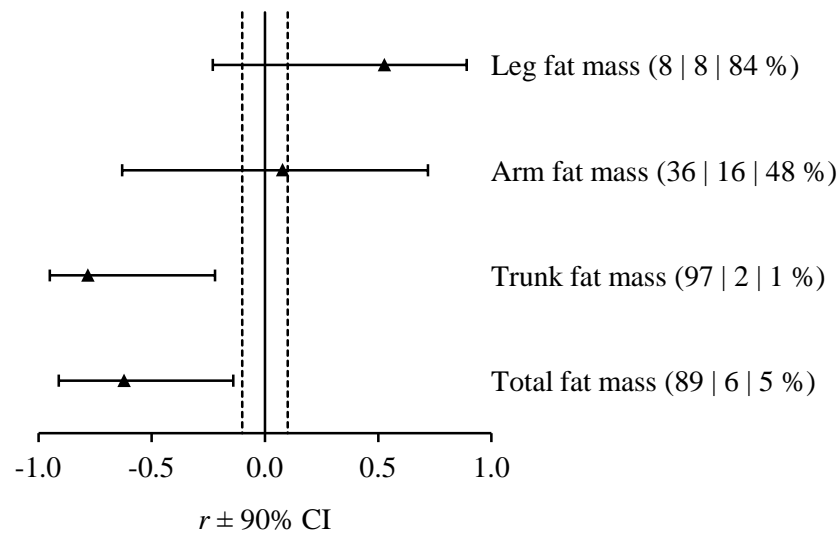


Figure 6.1. Correlation coefficients (r) for the relationships between mean fat masses and absolute TEMs for each sub-group ($n = 7$), at a whole body and region level. Bars represent 90% CI. Central area ($r = 0.0 \pm 0.1$) indicates trivial relationships. Percentages in brackets represent likelihoods that relationships are negative | trivial | positive.

6.3.2. Body composition changes across a season

The longitudinal body composition changes exhibited by skeleton athletes are illustrated in Figure 6.2. Many changes were above the TEM threshold, and thus can be considered ‘true’ body composition changes. Five out of seven elite squad skeleton athletes and all five talent squad skeleton athletes exhibited increases in both lean mass (ranging from 2.3 to 6.9%) and leg lean mass (ranging from 3.5 to 10.9%) between the first two scan time points (across training block 1 for the elite athletes and the entire training season for the talent squad athletes, respectively). Decreases in total fat mass (ranging from -12.3 to -17.1%) were also observed for six athletes across this period and total body mass also decreased across this period for two of these six athletes. Only one athlete (talent squad) exhibited an increase, above the associated TEM threshold, in total fat mass (15.0%) between the first two scan time points.

Across the second half of the training season (block 2), four elite squad athletes exhibited decreases (ranging from -2.1 to -4.3%) in lean mass and leg lean mass also decreased in two athletes (-3.8 and -4.3%). Only one elite athlete exhibited an increase (9.8%) in fat mass across the second half of the training season. Conversely, two elite athletes were found to have increased lean mass (2.2 and 2.4%) and three were observed

to have decreased fat mass (-8.9, -9.1 and -10.1%) across block 2. Across the competition season (i.e. from the end of training block 2 to the end of competition season), seven out of 13 skeleton athletes exhibited decreases in lean mass (ranging from -2.0 to -7.7%) and fat mass increases (ranging from 9.4 to 24.8%) were observed in nine of the athletes across this period. Leg lean mass was also found to have decreased (ranging from -5.6 to -8.3%) across the competition period in three athletes.

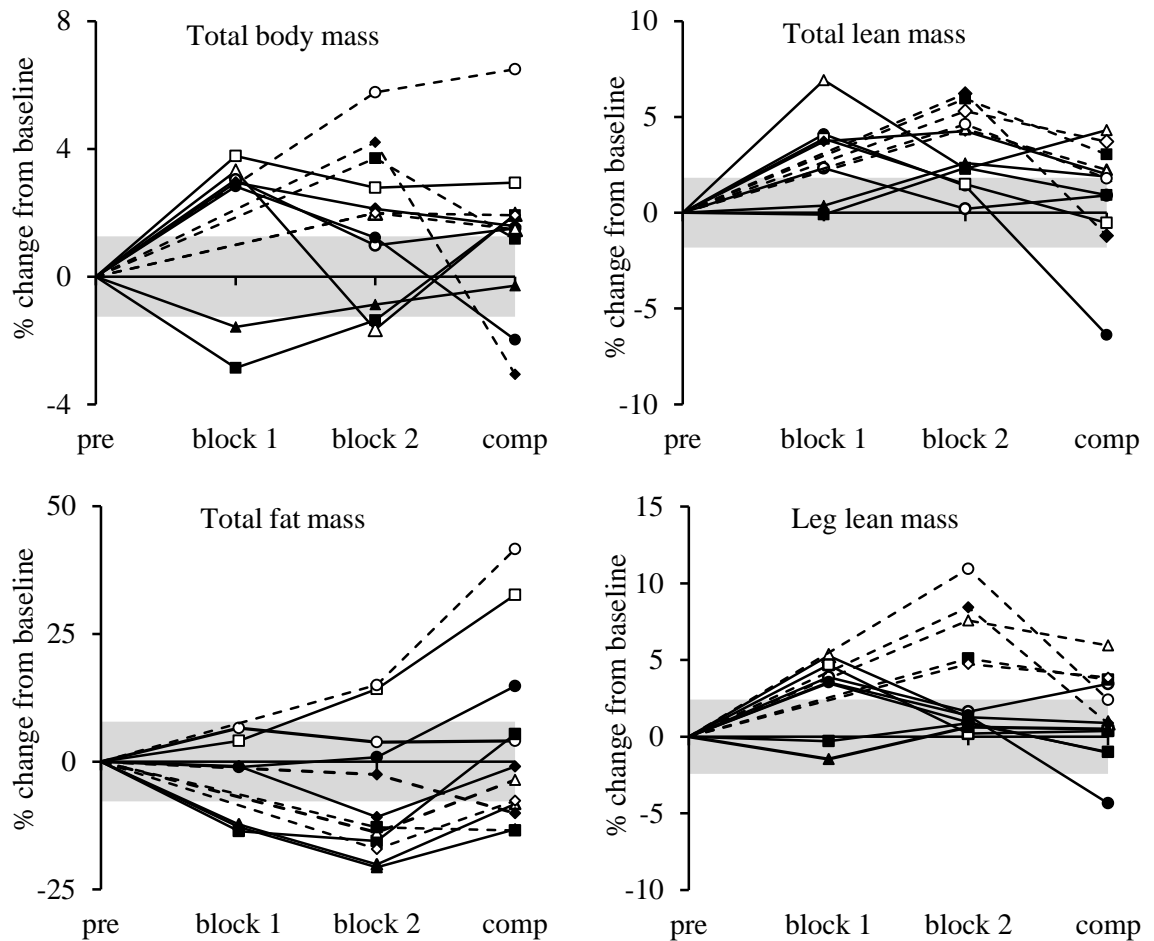


Figure 6.2. Longitudinal changes in body composition from baseline (pre) exhibited by individual skeleton athletes across two training blocks (block 1 and 2) and one competition block (comp). Shaded areas represent the TEM threshold (TEM doubled) for each body composition measure from baseline. Solid lines represent elite squad and dashed lines represent talent squad skeleton athletes. N.B. talent squad athletes underwent one 24 week training block, instead of the two 12 week blocks (as for the elite squad).

6.3.3. Associations between body composition changes and performance

The relationships between the changes in body composition and physical performance for skeleton athletes (Pearson correlation coefficients \pm 90% CI and percentage likelihoods) are provided in Figure 6.3. Improvements in jump performance were positively related to increases in lean mass ($r = 0.53$, 90% CI = 0.23 to 0.74) and leg lean mass ($r = 0.59$, 0.32 to 0.77). Relationships between lean mass changes and leg press performance changes were less certain, however, clear positive relationships were still observed ($r = 0.35$, 90% CI = 0.04 to 0.60 for lean mass and $r = 0.33$, 0.01 to 0.59) for leg lean mass). Increases in fat mass were associated with decreases in both jump ($r = -0.44$, 90% CI = -0.66 to -0.12) and leg press ($r = -0.37$, -0.62 to -0.06) performance.

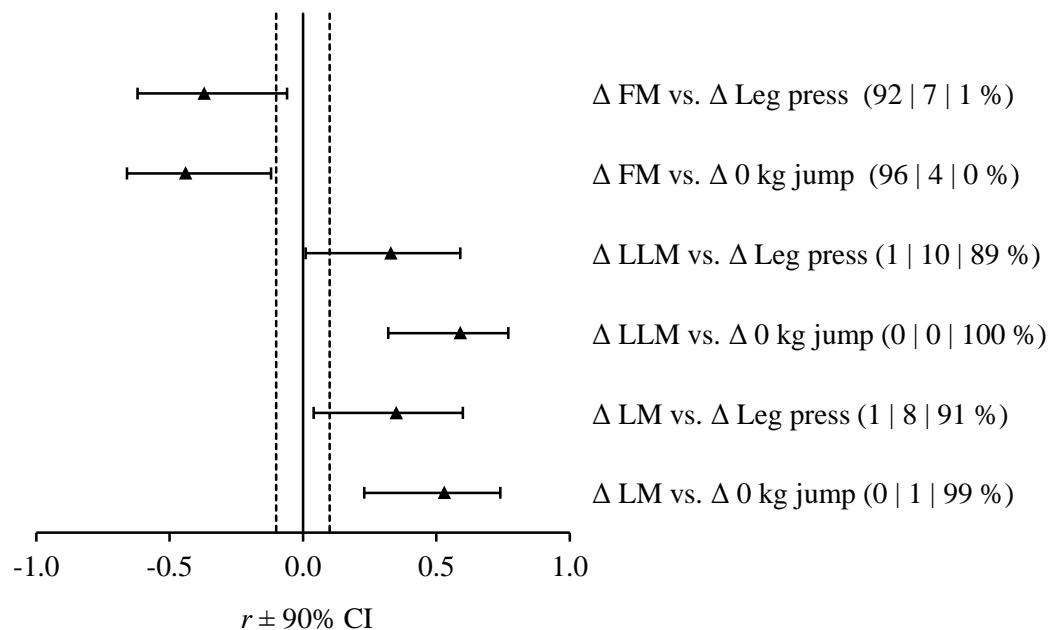


Figure 6.3. Correlation coefficients (r) for the relationships between percentage changes in body composition and physical performance (0 kg jump and leg press) in 12 skeleton athletes. Bars represent 90% CI. Central area ($r = 0.0 \pm 0.1$) indicates a trivial relationship. Percentages in brackets represent the likelihoods that the relationships are negative | trivial | positive. FM, LLM and LM denote fat mass, leg lean mass and lean mass, respectively.

6.4. Discussion

The purpose of this study was to firstly quantify the reliability of DXA in a large and diverse cohort of athletes by conducting repeated scans across a short period of time, within which actual body composition changes are unlikely to occur. Subsequently, using the typical errors of the measurement, this study aimed to evaluate the longitudinal changes in body composition and explore the performance implications of these changes. The key finding was that many ‘true’ longitudinal changes in body composition (above the typical error threshold) were detected and seemed to align with the primary training emphases. These changes appeared to be practically meaningful, as increases in lean mass and decreases in fat mass were associated with improvements in two measures of strength and power. Conversely, a loss of lean mass and an accumulation of fat mass (typically observed across the competition season) were found to be detrimental to physical capacity.

The meticulously controlled scanning protocol which was previously advocated by Nana et al. (2012, 2013) can be very challenging in reality. Thus, an important first step was to quantify the typical errors in the DXA measurements in the applied athletic setting. This more realistic approach resulted in larger whole-body and regional TEMs compared with those in the aforementioned studies where athletes were immediately reassessed using a highly controlled scanning protocol (Nana et al., 2012, 2013). For example, the TEM for whole body mass was greater in the current study (0.6%) compared with that of previous studies (0.1 - 0.4%; Nana et al., 2012; Nana et al., 2013). The introduction of biological variation (differences in hydration status, food consumption and physical activity) is likely accountable for these differences as each of these factors have been found to introduce measurement errors in the DXA estimates (Horber et al., 1992; Pietrobelli et al., 1998; Nana et al., 2012, 2013). In fact, the errors reported in the current study were similar to those observed when food consumption and physical activity were not restricted. For example, TEMs of 0.6% and 0.4% for total body mass have been reported after 24 hours of uncontrolled daily activities and an exercise session, respectively (Nana et al., 2012, 2013).

The observed high ICCs suggested good agreement between the DXA estimates of repeated scans for all body composition measures. However, as with any correlational measure, the strength of this relationship may have been influenced by the

heterogeneous nature of the sample (Weir, 2005). For example, total lean mass varied from 36.6 to 99.8 kg across the entire cohort and so this high inter-subject variability may result in an artificially high ICC. Correlational measures also do not provide information about the magnitude of the errors and thus, as previously suggested (Hopkins, 2000a), typical errors of measurements are perhaps more informative when attempting to understand the precision of DXA measurements.

In line with previous research (Mazess et al., 1990; De Lorenzo et al., 1997; Nana et al., 2012, 2013), errors were higher for individual region masses (1.4, 1.0 and 1.6% for total masses of the trunk, legs and arms, respectively) compared with those at a whole body level (0.6%). This is likely to be a result of the cancelling out of regional errors to some extent when the individual region masses are summed. Fat masses appear to be more sensitive to variation than the total and lean masses (with trunk and arm fat most variable), in support of previous findings (Mazess et al., 1990; Nana et al., 2012, 2013). Horber et al. (1992) and Pietrobelli et al. (1998) found that the larger errors in DXA estimated fat masses are somewhat related to variance in soft tissue hydration. However, it has been suggested that these errors do not substantially impact the accuracy of DXA fat estimation within normal physiological ranges (Pietrobelli et al., 1998) and other error sources (for example variation in the partitioning of body regions and data extrapolation) may be responsible for the greater variation in fat mass estimation in these body regions.

The DXA system uses only a 2D image to estimate the 3D composition of the body by determining the degree of X-ray attenuation in each image pixel. Soft tissue composition can be solved only in bone-exclusive pixels. Thus, algorithms within the DXA software must extrapolate these bone-containing pixels to estimate the soft tissue that is directly above and below these pixels in the image. In the trunk region, there are many bone containing pixels (i.e. for the spine and rib cage) and the composition is more complex than other regions (due to the inclusion of organs). Thus, a greater degree of extrapolation is required, which may somewhat explain the greater measurement errors observed for the trunk compared with other regions. Additionally, food consumption has been shown to introduce further variability in the detected composition of this region (most likely due to the presence of additional matter in the digestive

system), however, this appears to be dependent on both the timing and content of the meal (Nana et al., 2012).

The repeatability of fat mass estimation by DXA appears to be related to the individual characteristics of the athlete with differences detected between athlete sub-groups in this study. Total fat mass seems to influence fat mass errors with larger whole body and trunk fat mass errors observed in the leaner individuals (Figure 6.1). As whole-body measures are simply the sum of regions, it appears that the variation in total fat mass is likely attributable to errors in trunk fat mass estimation. The aforementioned algorithms in-built in the DXA system software have been optimised for individuals with average adiposity. Thus, the stability of these equations to estimate fat masses at the extremes of this scale (e.g. obese or very lean individuals) may be compromised (Stewart and Hannan, 2000b). This provides an explanation for the finding that trunk fat mass errors are inflated in extremely lean individuals, compared with those individuals who possess greater adiposity (e.g. the rugby sub-group in this study) and may resemble the average population more closely. In fact, Stewart and Hannan (2000b) reported zero fat in the trunk region in three very lean athletes which the authors acknowledged as practically impossible given the essential lipids present in certain organs. To the author's knowledge, the current research is the first study to explore these relationships which, especially for the trunk fat mass, warrant consideration when tracking body composition changes in particularly lean individuals.

Many of the body composition changes exhibited by the skeleton athletes in this study were shown to be greater than the measurement errors associated with this scanning protocol. Thus, DXA appears to provide a sufficiently sensitive tool to detect 'true' changes in body composition in the applied setting. Longitudinal changes in body composition were found to be extremely individual (Figure 6.2) despite the same primary training emphases within athlete groups. However, across the first block of the skeleton training season, where athletes were undertaking strength training primarily focussed on hypertrophy (Figure 4.1), the majority of athletes (10 out of 12) exhibited increases in total body, lean and leg lean masses which are typical responses to this type of training (Kraemer et al., 1988). As the main contributor to force production is lean (specifically muscle) mass (Maughan et al., 1983; Bruce et al., 1997), the described changes are likely to be favourable to skeleton start performance. The apparent larger

increases in lean masses exhibited by the talent athletes compared with the elite athletes are likely due to differences in training histories between the two squads. This is because the rate of adaptation to training is known to be faster in untrained individuals (Rhea et al., 2003).

The reductions in total body mass exhibited by two athletes were a result of decreases in fat mass, with lean mass unchanged across this training block. Although the latter response may not fully reflect the hypertrophic emphasis of this training block, a decrease in fat mass and the maintenance of lean mass is likely to be beneficial to performance as the power-to-body mass ratio is probably improved. This effect has been reported previously with reductions in adiposity (decrease in skinfold measurements) associated with sprint performance improvements (Legaz and Eston, 2005). Four athletes who increased total body mass and lean mass were also found to decrease fat mass between the first time-points. This favourable response has been reported elsewhere, typically under carbohydrate-restricted dietary interventions, and may be mediated by reductions in circulating insulin (Krieger et al., 2006).

The emphasis of training for the elite squad was shifted towards higher velocity, sprint-based exercises in block 2 with a greater number of running drills and push-start practice sessions than in block 1 (Figure 4.1). This type of periodisation is typically employed by strength and conditioning coaches in explosive sports as it is considered to elicit greater increases in several strength and power measures (Harris et al., 2000). However, decreases in lean mass were observed in four athletes across this period, two of which also exhibited decreases in leg lean mass. Although this type of training is not associated with the same levels of hypertrophy as the heavy strength training block (Häkkinen, 1989), this response is undesirable due to the likely detrimental effect on the power-to-body mass ratio which underlies all sprint-based performances (Cronin and Hansen, 2005). The only instance where a decrease in lean mass may not negatively influence physical performance would be if the athlete concomitantly reduced fat mass to counteract this effect, and thus, preserve the power-to-body mass ratio. One athlete exhibited a further unfavourable body composition change across this training block, with an increase in fat mass accompanying the decreases in lean mass and leg lean mass. As a consequence, the maximum rate at which an athlete can accelerate their CM is theoretically slowed through the combination of a decline in force production

capacity and an increase in ‘passive’ mass. Strength and conditioning coaches should perhaps strive to prevent these body composition changes by placing more emphasis on the maintenance of lean mass when shifting from a heavy strength training block to higher velocity based training blocks, as was the case for this training season (Figure 4.1).

Across the competition season six elite and three talent squad skeleton athletes exhibited increases in fat mass, indicative of positive energy balance (Alligier et al., 2012). It may be noteworthy that amongst the talent squad skeleton athletes (who were competing on either the European or North American circuits for the entire competition season) two out of the three athletes who experienced ‘true’ increases in fat mass across the competition season were those competing on the North American circuit. This may be related to a difference in access to training facilities on the different competition circuits, although similar decreases in lean mass were observed across all athletes. Alternatively, these observations may indicate differences in energy intake between these groups of athletes. As dietary intake was not recorded, we can only speculate that this may be a consequence of different dietary practices among athletes competing on the North American and European circuits.

The majority of athletes also exhibited decreases in lean mass across the competition season, suggesting a negative protein balance (i.e. breakdown > synthesis). This is likely to be a detraining response (Mujika and Padilla, 2001), but may also reflect insufficient protein intake (Phillips, 2004). A reduced training load is typically experienced across this phase of the season, which may be somewhat prescribed (Le Meur et al., 2012), but may also be due to the reduced access to facilities when travelling on the competitive circuit. Additionally, one talent squad athlete appeared to be in negative energy balance with reductions in fat mass, lean mass and total body mass across the competition season. Insufficient macronutrient intake, together with exposure to stresses such as travel or environmental conditions (Le Meur et al., 2012), may have contributed to this response. In fact, exposure to altitude (> 5000 m) and hypoxic conditions has been associated with reductions in body weight, and notably, fat free mass (Wing-Gaia, 2014). This seems to be a result of perturbations in appetite regulation (Snyder et al., 2008), impaired muscle protein synthesis (Viganò et al., 2008) and increases in muscle protein breakdown (Holm et al., 2010). Although the conditions

experienced by skeleton athletes may be less extreme than those in the aforementioned altitude studies (races can take place at altitudes of 1000-2000 m; FIBT, 2015b), it is conceivable that these effects could be observed to some extent across the skeleton competition season. Coaches and sports scientists should be aware of these trends across the competitive season and attempt to implement appropriate nutritional or training interventions to prevent these detrimental effects. Nonetheless, it does appear possible to induce a sufficient training stimulus and match energy requirements to dietary intake on the competitive circuit, as one elite athlete appeared to maintain all body composition measures across this block.

Body composition contributes to explosive performance by influencing the crucial power-to-body mass ratio that underlies many athletic movements (Cronin and Hansen, 2005). Previously, the impact of body composition changes on physical performance was largely unexplored in the context of many sports. This study showed that increases in both lean mass and leg lean mass were associated with increases in lower limb strength and power, likely due to the association between muscular cross-sectional area and force production (Maughan et al., 1983; Bruce et al., 1997). Conversely, fat mass accumulation is likely to reduce the power-to-body mass ratio (if this increase outweighs any simultaneous increase in lean mass). Indeed, this study reported increases in fat mass to be related to reductions in both physical performance measures, supporting the detrimental effect of fat mass accumulation on explosive performance.

6.4.1. Conclusion

This study investigated the typical errors involved in the estimation of athletes' body composition by DXA in the applied setting. Higher errors were observed compared with those in the previous literature when meticulous protocols are followed, with regional fat masses the most variable. However, this study showed that 'true' body composition changes (as evaluated using a threshold of 2 x TEM) in response to specific training emphases can still be detected by DXA, even when a less stringently controlled approach is adopted. Thus, this study reveals DXA as an appropriate tool to obtain useful information about the current status and development of skeleton athletes in the applied setting. Unfavourable physique changes (increases in fat mass and sometimes concomitant decreases in lean mass) were typically observed across the competition season emphasising the importance of monitoring skeleton athletes' body composition

across this phase. Importantly, these changes in body composition were related to physical performance measures. Fat mass accumulation was confirmed to be detrimental to strength and power, whereas lean mass accrual was associated with enhancements in physical capacity. Overall, this study has emphasised the potentially important influence of body composition on strength and power indices and the ability of DXA to detect these meaningful changes, and thus, to inform the training process.

CHAPTER 7: INVESTIGATING CHANGES IN SLED VELOCITY ACROSS THE START PHASE

Part I: Start Performance Determining Aspects of the Sled Velocity Profile

7.1. Introduction

A fast start is widely considered to be a prerequisite for success in skeleton (Zanoletti et al., 2006). However, surprisingly, the development of sled velocity during a skeleton push-start has not yet been studied in depth. For example, only discrete measures such as dry-land push-track split times (10, 15, 20, 25, 30 m from the starting block; Sands et al., 2005) and velocities (15 m and 38-45 m from the starting block, Chapter 4), as well as ice-track 15 and 45 m velocities (Bullock et al., 2008), have been reported to date. Such performance measures are limited by the fact that potentially important transient changes in sled velocity (for example during the loading phase) are difficult to detect.

In Chapter 4, physical test scores were found to consistently explain more of the variance in pre-load velocity (15 m mark) than post-load velocity (38-45 m). This may implicate other determinants (in addition to the physical attributes) of skeleton start performance, which could be related to the loading phase. High correlations ($r = 0.71$ and 0.67 ; Sigulda and St. Moritz ice-tracks, respectively) have previously been reported between 15 and 45 m velocities (Bullock et al., 2008). However, some unexplained variance exists which is conceivably due to variation in loading phase success and/or downhill running ability. In order to investigate such speculation, a more detailed analysis of sled velocity during the start phase is required.

Therefore, the aims of this study were to characterise the development of sled velocity across the start phase and to investigate how different aspects of the sled velocity profile contribute to performance.

7.2. Methods

7.2.1. Participants

The same British skeleton athletes who participated in Chapter 4 were also involved in this study, except for one male talent squad athlete who was no longer part of the programme. Thus, data were collected for thirteen athletes (4 female and 3 male elite

squad athletes; 1 female and 5 male talent squad athletes). The mean age, height and mass of the athletes recorded at the start of the testing period are presented in Table 7.1. The University of Bath Research Ethics Approval Committee for Health provided ethical approval for this study to be conducted and all athletes provided written consent for data to be collected during a series of push-track and physical testing sessions described in Chapter 4.

Table 7.1. Descriptive characteristics for the 13 skeleton athletes (mean \pm SD).

	Height (m)	Mass (kg)	Age (yr)
Male elite squad (n = 3)	1.79 \pm 0.10	84.0 \pm 6.9	26 \pm 2
Female elite squad (n = 4)	1.71 \pm 0.02	68.3 \pm 3.0	24 \pm 2
Male talent squad (n = 5)	1.75 \pm 0.05	75.1 \pm 7.4	22 \pm 1
Female talent squad (n = 1)	1.58	56.8	21

7.2.2. Data collection

An individualised, athlete-led 30-minute competition warm-up was performed prior to each testing session consisting predominantly of running and jumping drills, and stretching. Testing was conducted as part of the ongoing athlete monitoring protocol described in Chapter 4, section 4.2.2. Each push-start trial was performed from the athletes' preferred starting side, with a recovery period of at least three minutes between efforts. Participants did not complete any vigorous training in the 36 hours leading up to each testing session. Push-starts were performed by pushing a wheeled sled on an outdoor dry-land push-track at the University of Bath, as previously described in Chapter 4. The wheels of the sled ran along metal rails which were embedded into the surface of the track. A photocell interrupter arm was attached to, and protruded (~0.35 m) the front of, the sled to provide a consistent triggering point across the track. This was to overcome the aforementioned (section 4.2.2) issue surrounding different body parts triggering the permanent photocell system at the push-track. One of the sled wheels was instrumented with a custom-built magnet encoder (Sleed; UK Sport, Sheffield Hallam University) which provided the time interval for each complete turn of the wheel (every 0.1984 m). Sleed data were telemetrically transferred to a receiver and combined with data from the permanent photocell system (Tag Heuer, Switzerland; 0.001s accuracy). Both data sets were stored using custom-built software (Sleed; UK Sport, Sheffield Hallam University). The Sleed software recognised when the velocity

of the sled exceeded $2 \text{ m}\cdot\text{s}^{-1}$ and the permanent photocell system provided two reference points (Figure 7.1). The triggering of the 5 m photocell adjusted the distance data (visible in the Sled system data) to 5 m, and data collection terminated when the sled interrupted the final photocell at the 55 m mark. The 15 m and 55 m photocell times were also recorded by the permanent photocell system. A Sony HC9 video camera (50 Hz at $1/600 \text{ s}$ shutter speed) was located next to the track at about 10 m (from the starting block) and panned to capture footage of the entire start phase. The number of steps taken before loading in each push-start trial was recorded from the video footage.

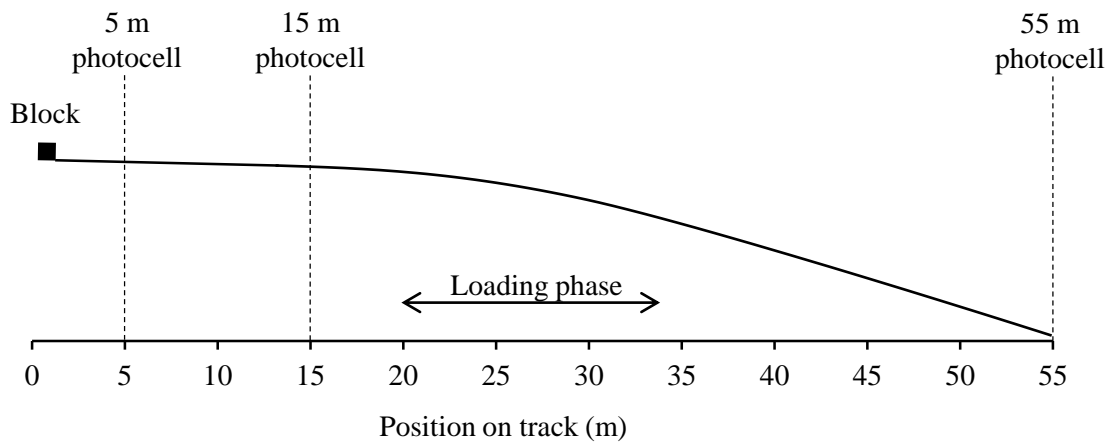


Figure 7.1. Schematic representation of the push-track set-up.

7.2.3. Sled velocity data processing

Raw sled velocity data were exported from the Sled software and velocity-distance profiles were plotted for each trial. Data were not filtered because time intervals were irregular and thus, do not allow a digital filter to be used (Robertson et al., 2004). Additionally, there appeared to be minimal noise within the data. As noise becomes more problematic only when higher order derivatives are computed (Winter et al., 1974), which was not the case in this study, data smoothing was not considered to be necessary in this study. There was, however, some evidence of wheel slippage (an artificial drop in velocity for typically 2 or 3 consecutive points) at set points of the track. This usually occurred on one or two occasions per trial, predominantly in the post-load phase. These data points were excluded from the data set (as opposed to linearly interpolating between points) as this was shown to make very small differences to sled velocities at set distances from the block ($< 0.01 \text{ m}\cdot\text{s}^{-1}$) and the distances

recorded (< 0.05 m). This is because the errors in sled velocity are isolated to the wheel turns in question and sled velocity data calculated across the subsequent wheel turns remain unaffected (only very small errors in position data are observed). Additionally, as the post-load phase was terminated when the 55 m photocell was interrupted, the sled velocity recorded for the final wheel turn was assumed to be 55 m mark velocity. A typical sled velocity profile is illustrated in Figure 7.2. Two events surrounding the loading phase were defined as follows:

Pre-load Final data point before a decrease in velocity (indicative of the end of the initial acceleration phase and the start of the loading phase; Figure 7.2)

Post-load First data point after the load following which the rate of acceleration is approximately constant (no further propulsion from the athlete and thus, it can be assumed that the athlete is in the prone driving position; Figure 7.2)

The velocity and distance of the sled at the above time points were recorded to provide pre-load velocity, pre-load distance, post-load velocity and post-load distance. Additionally, the time and distance between the two events were calculated and defined as ‘load duration’ and ‘load length’, respectively.

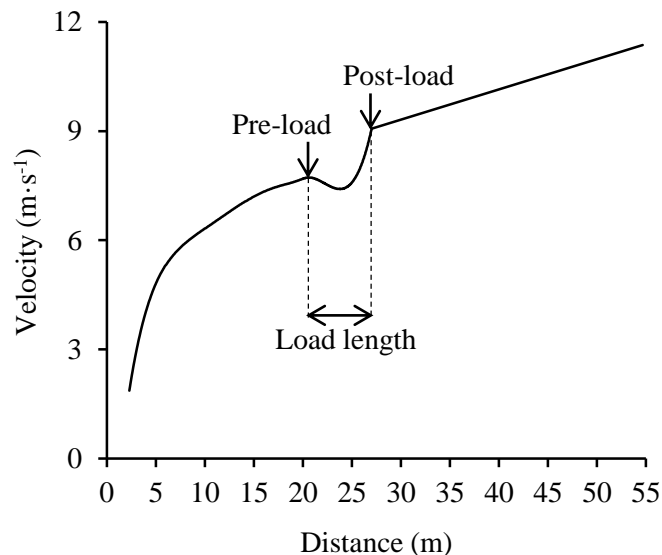


Figure 7.2. A schematic sled velocity profile during a skeleton push-start and the identification of the pre-load and post-load time points. N.B. Load duration was calculated across the same section as load length.

A sixth-order polynomial was fitted from the first data point to ten points following the pre-load time point. This method was preferable to data padding techniques (e.g. linear extrapolation and reflection; Smith, 1989) as, based on visual inspection, these other techniques seemed to result in clear and visible errors towards the end-points. The equation of the sixth-order polynomial was used to calculate sled velocity every 2.5 m across the pre-load section of the track (0-25 m from the block). As acceleration is practically constant following the loading phase (due to a constant track gradient and minimal changes in friction and air resistance), a linear trend line was fitted to the data from the post-load point to the final data point.

Velocity drop during the load was defined as the greatest negative change in velocity across the loading phase (between the pre-load and post-load data points; Figure 7.3). Load effectiveness was calculated by extrapolating the post-load linear trend line to the pre-load distance and computing the difference between this extrapolated velocity and the actual pre-load velocity (Figure 7.3.)

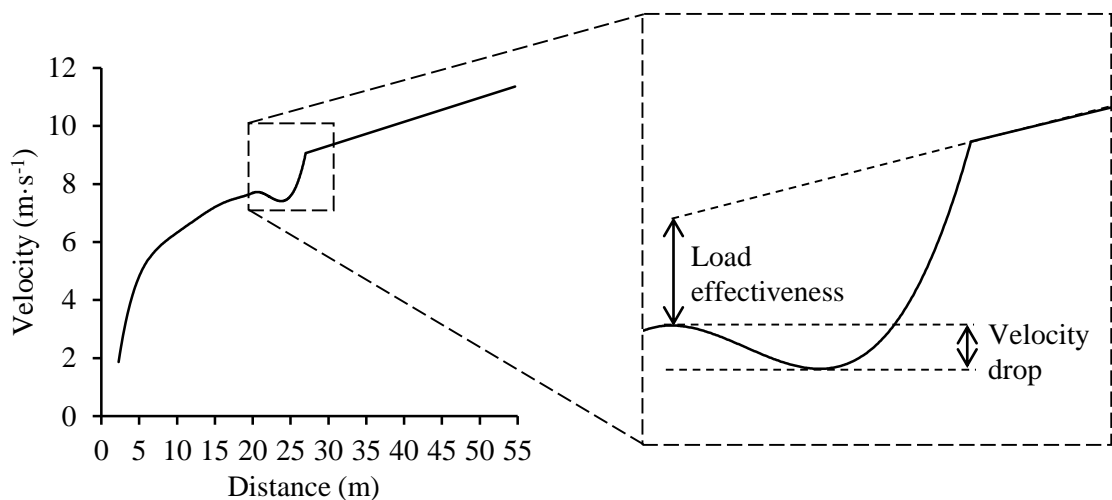


Figure 7.3. A schematic illustrating the methods used to determine velocity drop and load effectiveness.

As previously proposed by Bezodis et al. (2010), measures of performance for discrete sections of sprint-based events should encompass both time and velocity measures. This is because it is unclear whether a more favourable performance is one in which an athlete covers the discrete phase in a shorter period of time or whether attaining a higher velocity at the end of the phase is more beneficial to overall performance. Although

15-65 m start times are routinely used to evaluate start performances in competition, the velocity at the 65 m mark should also be considered as this determines the ‘potential’ velocity an athlete can attain in the subsequent driving phase. For example, skeleton athletes with identical 15-65 m start times may be differentiated by their velocities at the end of the start phase. A measure of overall sled acceleration is, therefore, perhaps the most appropriate measure of skeleton start performance in the current study.

An important difference between skeleton push-starts and conventional sprint starts, however, is that the official start of the run in skeleton is the 15 m mark, rather than a starting signal initiating the race from the starting blocks (such as in athletic sprinting). Therefore, the time taken to reach 15 m does not directly contribute to overall performance and theoretically an athlete can take a longer period of time in the first 15 m in order to attain a higher 15 m velocity. For example, an athlete may try to use longer ground contacts in an effort to increase horizontal net impulse and thus velocity. In fact, previously reported ‘imperfect’ correlations between the 15 m time and 15 m velocity support the notion that athletes achieve different sled velocity profiles in this initial section of the track (Bullock et al., 2008). Thus, to encompass both of the above start performance measures into a single measure of start performance, the following ‘sled acceleration index’ was formulated:

$$\text{Sled acceleration index} = \frac{55 \text{ m velocity}}{15-55 \text{ m time}} \quad [7.1]$$

N.B. 15-55 m time and 55 m velocity are included here as proxies for start time (15-65 m) and 65 m velocity, respectively, as the dry-land push-track allows data to be collected across this distance only.

7.2.4. Statistical analysis

In order to assess the ability of the start performance descriptors to predict overall start performance, stepwise multiple regression analysis was conducted. Predictor variables included number of steps, pre-load velocity, pre-load distance, load duration, load length, velocity drop and load effectiveness with the criterion variable being the sled acceleration index. Standardised β weights allowed for the comparison of the relative explanatory power of the predictors on the criterion. Post-load distance and post-load velocity were not included in the model in order to minimise the number of predictor

variables, and therefore, maximise statistical power. Additionally, the post-load measures were considered to be unlikely contributors to the predictive model, as these can be largely explained by the pre-load conditions and loading phase variables.

As the number of elite athletes available to participate in this study is inevitably small, multiple data points from each athlete were included in the regression analysis (a total of 35 data points from three testing sessions). This may introduce some dependence between data points or clustering of residuals, and could potentially compromise the statistical vigour of this procedure. However, to truly obtain insight regarding elite skeleton start performance, the methods presented here are a necessary compromise providing that the limitations are acknowledged and tested as rigorously as possible. To ensure that any potential autocorrelation did not significantly impact the model, the Durbin-Watson statistic and homoscedasticity tests were used to assess for correlation between, and the consistency of, the residual errors, respectively. Entered variables remained in the model if a significant R^2 (or F -ratio) change was reported. Variance inflation factors (VIFs) were used to assess the level of collinearity between the independent variables.

Means and standard deviations were calculated for each start performance descriptor (number of steps, pre-load velocity, pre-load distance, post-load velocity, post-load distance, load length, load duration, velocity drop and load effectiveness) for each athlete. For all physical test scores undertaken at the same time points as push-starts, means and standard deviations were calculated for each athlete. Pearson correlation coefficients were computed for the relationships between the mean values ($n = 13$) of three key physical test scores (as identified in Chapter 4; 0 kg jump height, Keiser FP_{\max} and unresisted 15 m sprint time) and the mean start performance descriptors. Confidence intervals ($\pm 90\%$ CI) for all correlation coefficients were calculated and magnitude-based inferences were derived as previously recommended (Batterham and Hopkins, 2006), using the associated spreadsheet (Hopkins et al., 2009). The magnitudes of the correlation coefficients were interpreted in exactly the same way as in previous chapters (see section 3.2.4 for full details).

7.3. Results

A Durbin-Watson statistic of 1.5 indicated that the level of autocorrelation within the data set was within the acceptable limits (Field, 2000) and homoscedasticity and normality tests revealed consistent and normally distributed residuals. Variance inflation factors were found to be well below the threshold of 10 (VIFs ranged from 1.5 to 3.7), which is generally considered to indicate problematic levels of multicollinearity (Hair et al., 2009). Thus, the data set was found to be appropriate for the regression analysis. Four variables (pre-load distance, pre-load velocity, velocity drop and load effectiveness) were revealed as significant contributors (significant F -ratio change; $p < 0.05$) to the prediction of the sled acceleration index (Table 7.2). The three variables which were excluded from the model (i.e. those which did not significantly improve the overall fit) were number of steps before loading, load duration and load length. The overall fit of the model was highly significant ($r = 0.99$), and thus, these four variables were found to explain 99% of the variance in start performance.

Table 7.2. Regression model summary for the prediction of the sled acceleration index.

Model	Variables entered	R	R^2	Change statistics		
				R^2 change	F change	Sig.
1	Pre-load velocity	0.84	0.71	0.71	80.7	0.000
2	Pre-load distance	0.97	0.93	0.22	109.2	0.000
3	Load effectiveness	0.99	0.98	0.05	86.4	0.000
4	Velocity drop	0.99	0.99	0.01	7.6	0.016

Pre-load velocity was found to explain the greatest portion of explained variance in the sled acceleration index (71%) and therefore appears to have the highest predictive power out of the four performance descriptors. Pre-load distance and load effectiveness explained an additional 22 and 5% of the variance in the sled acceleration index, respectively. Velocity drop was revealed as the least predictive of the sled acceleration index (1% explained variance), however, the inclusion of this variable still significantly increased ($p = 0.016$) the fit of the model. The standardised β weights for the four predictive variables (providing the degree to which each predictor affects the outcome variable, when all the effects of the other predictors are held constant) are presented in Figure 7.4. Higher pre-load velocity and load effectiveness were associated with start performance (standardised β weights = 1.70 and 0.25, respectively), whereas a longer

pre-load distance and a larger velocity drop were negatively related to the sled acceleration index ($\beta = -0.81$ and -0.07 , respectively).

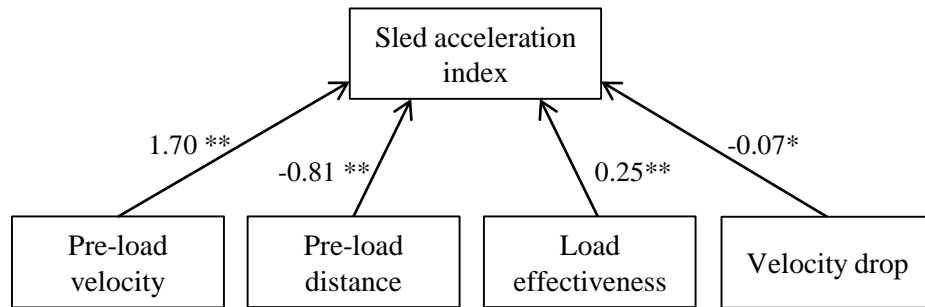


Figure 7.4. A model illustrating the predictors (standardised β weights) of skeleton start performance (sled acceleration index). * denotes significant contribution ($p < 0.01$) to the model. ** denotes significant ($p < 0.001$) contributions to the model.

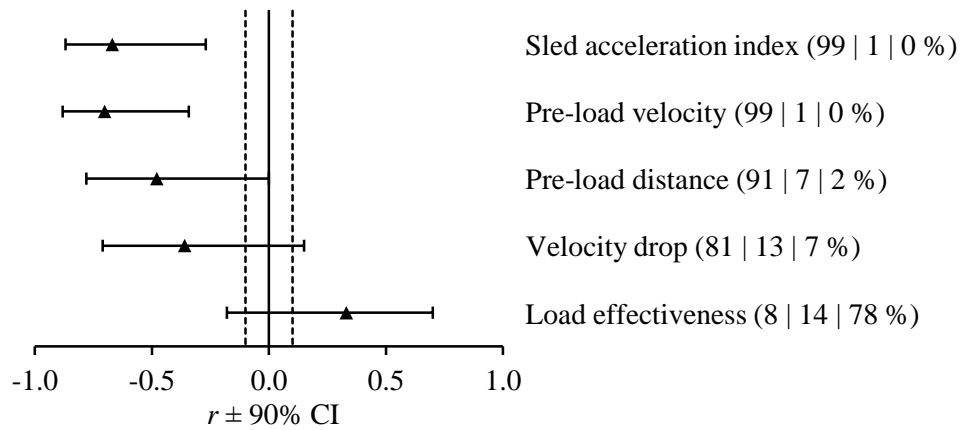
The unstandardised β weights can then be used to form the following regression equation (7.2), in which variables can be entered to predict the sled acceleration index (SAI):

$$SAI = (0.487 \times \text{Pre-load velocity}) - (0.055 \times \text{Pre-load distance}) + (0.239 \times \text{Load effectiveness}) - (0.067 \times \text{Velocity drop}) - 0.125$$

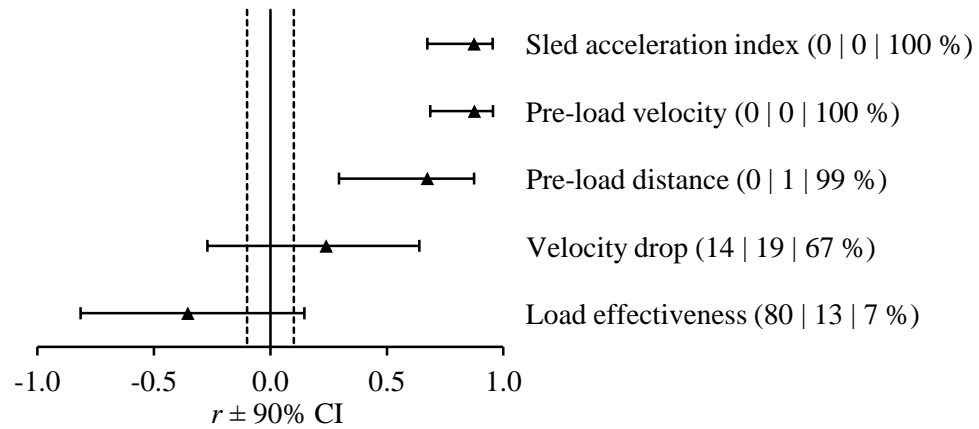
[7.2]

Several clear relationships were observed between start performance descriptors and the three physical test scores (Figure 7.5). Unresisted 15 m sprint times were negatively related to pre-load distance ($r = -0.48$, 90% CI = -0.78 to 0.00), pre-load velocity ($r = -0.70$, -0.88 to -0.34) and the sled acceleration index ($r = -0.67$, -0.87 to -0.27). Further, max CM_{disp} under 0 kg load was found to be positively related to pre-load distance ($r = 0.67$, 90% CI = 0.29 to 0.87), pre-load velocity ($r = 0.88$, 0.69 to 0.96) and the sled acceleration index ($r = 0.87$, 0.67 to 0.95). Additionally, a clear positive relationship was found between Keiser FP_{max} and pre-load distance ($r = 0.40$, 90% CI = -0.09 to 0.74). Unclear relationships were observed between Keiser FP_{max} and both pre-load velocity and the sled acceleration index. Interestingly, unclear relationships were also observed between all three physical test scores and the loading phase performance descriptors (velocity drop and load effectiveness).

a) Unresisted sprint 15 m time



b) Max CM_{disp} - 0 kg load



c) Keiser FP_{max}

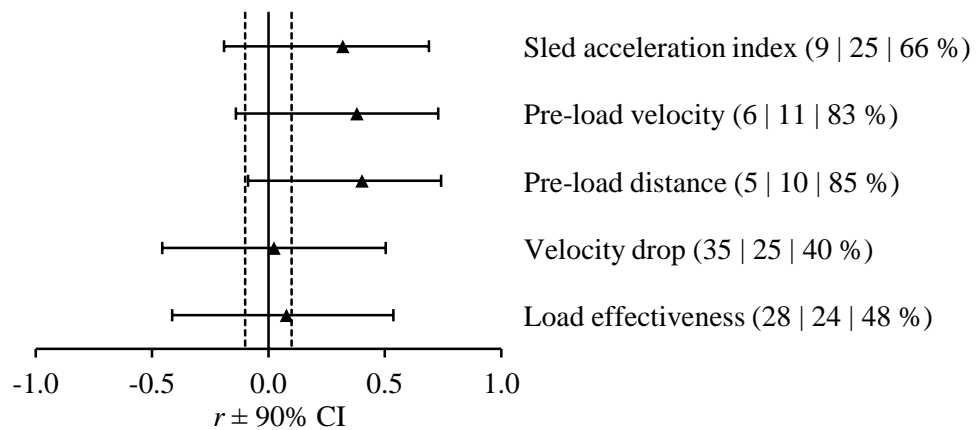


Figure 7.5. Pearson (r) correlations between three physical characteristics (Unresisted sprint time, Max CM_{disp} - 0 kg load and Keiser FP_{max}; a), b) and c), respectively) and five start performance descriptors. Bars represent 90% CI. Central area ($r = 0.0 \pm 0.1$) indicates a trivial relationship. Percentages in brackets represent the likelihoods that the relationships are negative | trivial | positive.

7.4. Discussion

To the author's knowledge, this is the first study to investigate the velocity profile of the sled during the skeleton push-start. The instrumented sled wheel provided a unique opportunity to study the transient sled velocity changes during dry-land practice push-starts in greater detail than was previously possible. The purpose of this study was to understand which aspects of the sled velocity profile are related to superior start performance. Higher pre-load velocity and load effectiveness both positively contributed to start performance. Additionally, loading the sled earlier and exhibiting a lower velocity drop during the loading phase were associated with superior starts.

Multiple regression analysis allowed the individual effects of the start performance descriptors on overall start performance to be evaluated. Four variables (pre-load velocity, pre-load distance, velocity drop and load effectiveness) were shown to independently contribute to the overall success of the start with high pre-load velocity revealed as the most important factor. When considered collectively with the observed negative relationship between pre-load distance and the sled acceleration index, faster start phases are a consequence of loading the sled with high velocity as early on the track as possible. This likely stems from the fact that post-load sled acceleration is primarily dictated by gravity and friction alone (as no driving is required in this phase on the dry-land push-track). Thus, theoretically, if an athlete is able to attain the same pre-load sled velocity but load the sled earlier, then the subsequent increase in velocity (due to gravitational component) across the remaining start phase is maximised.

The results from the regression analysis illustrate the 'ideal model' which skeleton athletes and coaches should strive for. Long-term training should, therefore, be focussed on enhancing accelerative ability to not only increase an athlete's maximum running velocity, but to attain this earlier in the start phase. However, this may be an over-simplistic model as interactions are likely to exist between the start performance descriptors. In fact, for an athlete to increase pre-load velocity in the short-term (without an advancement in physical capacity), an increase in pre-load distance will typically need to occur. This is to increase the total number of ground contacts through which positive net impulse (in the direction of the track) can be produced in order to increase velocity. Indeed, Bullock et al. (2008) have previously reported moderate negative relationships between start time and the number of steps taken before loading on

ice-tracks ($r = -0.45$ at Lake Placid and -0.41 at Sigulda), suggesting that faster starters took a greater number of steps than their slower counterparts on ice. However, the model illustrated in Figure 7.4 also suggests that for every additional metre taken before loading the sled, the pre-load velocity increase should typically be greater than $0.11 \text{ m}\cdot\text{s}^{-1}$ in order to improve the sled acceleration index. This is likely related to the constant influence of gravity on the velocity of the sled following the brow. From the regression model, it may therefore be interpreted that skeleton athletes should accelerate the sled maximally from the block until the sled velocity increments do not surpass those due to the gravitational component (at which time the loading phase should have been initiated). However, this assumes that load effectiveness and the velocity drop during the loading phase are not affected by an increase in pre-load velocity. This could be an oversimplification of reality and will be investigated in part II of this chapter.

Human performance is inevitably limited and there will be a velocity at which an athlete can no longer generate positive net impulse (in the direction of the track) across progressively shorter ground contact periods. For this reason, physical capacity is likely to regulate the number of steps a skeleton athlete takes before loading the sled. Indeed, in Chapter 3, the athletes who were able to attain higher step frequency were those who took a greater number of steps on three tracks (r ranged from 0.69 to 0.73; Figure 3.1). Additionally, the two physical tests in the current study which were previously (Chapter 4) identified as the strongest predictors of overall start performance (unresisted sprint and countermovement jump performance), were also related to both the position ($r = -0.48$ and 0.67 , respectively) and velocity ($r = -0.70$ and 0.88 , respectively) of the sled at the pre-load time point. Logically, athletes who exhibit superior lower limb power and sprint ability seem to be able to accelerate the sled across a greater distance to attain higher pre-load velocity than their less physically developed counterparts. This may reflect underlying differences in the ability to generate large forces at high velocity (across shorter ground contacts), as this appears to be an important determinant of maximum speed in athletic sprinting (Weyand et al., 2000; Morin et al., 2012). In fact, a more ‘velocity-oriented’ force-velocity profile (Keiser leg press) appeared to be favourable for push performance in Chapter 4. As maximum running velocity is higher and ground contact times are shorter on declined compared with level surfaces (Weyand et al., 2000), force production at high velocity may be an even stronger determinant of start performance in skeleton.

The loading phase of the start independently contributed to start phase success. Specifically, load effectiveness was found to positively influence the sled acceleration index, whereas a negative relationship was observed between velocity drop and start performance (Figure 7.4). Thus, skeleton athletes should attempt to minimise the velocity drop and maximise the overall velocity increase across the loading phase. A potential mechanism for such effects could be limiting the extent to which an athlete 'pulls back' on the sled during this phase. Interestingly, the loading phase variables were not related to any of the physical test scores (Figure 7.5). Therefore, load effectiveness and velocity drop could perhaps be dependent on more technique-based aspects and specific loading technique training may be warranted. However, the underlying kinematic and kinetic determinants of superior loading technique and the efficacy of different training methods to optimise this phase, are yet to be explored.

7.4.1. Conclusion

To the author's knowledge, this study is the first to use a continuous sled velocity measurement to characterise the skeleton push-start. A unique sled acceleration index was formulated to overcome the issues associated with conventional start performance measures. Additionally, a number of start performance descriptors (related to the sled velocity profile) were defined and a regression model revealed four descriptors (pre-load velocity and distance, load effectiveness and velocity drop) to significantly contribute to performance. The importance to accelerate the sled more rapidly was apparent, along with the ability to minimise the velocity drop and maximise overall velocity increase across the loading phase. Additionally, this chapter suggested that skeleton athletes should ensure that the increments in sled velocity across the final steps before loading surpass the gravitational acceleration component. However, the influence of higher pre-load velocity on the loading phase is yet to be established but could conceivably be significant. A positive influence of strength and power capabilities on pre-load velocity, pre-load distance and the overall sled acceleration index reinforced the essential role of physical training in skeleton athlete development. Notably, although the loading phase independently contributed to the success of the start phase, physical ability did not seem to influence the success of the load and separate loading technique-based training may therefore be warranted.

Part II: The Influence of Altering Track Profile and Loading Distance on Start Performance

7.5. Introduction

Skeleton athletes have been previously shown to adopt individual starting strategies (number of steps and time to load) on ice-tracks (Bullock et al., 2008 and Chapter 3), as well as on a dry-land push-track (Chapter 3). Theoretically, a skeleton athlete should strive to maximise pre-load velocity (Figure 7.4) and load the sled when the velocity increments due to the influence of gravity surpass the acceleration produced by the athlete (as shown in part I of this chapter). However, this assumes that an athlete's load effectiveness is not influenced by pre-load velocity, an effect which is yet to be investigated. Therefore, the 'optimum' distances at which individual athletes should load the sled are, in fact, currently unknown and the potential scope to improve skeleton start performance through adapting loading distance remains largely unexplored.

It has been suggested that the unique characteristics of tracks (e.g. gradient, ice conditions and proximity of the first curve) influence the number of steps taken and time to load the sled (Bullock et al., 2008). For example, athletes were reported to take significantly fewer steps and to load significantly earlier on the steeper profile at St. Moritz (14 ± 1 steps and 3.60 ± 0.15 s to load) compared with the flatter profiles at Lake Placid (18 ± 1 steps and 4.38 ± 0.24 s to load) and Sigulda (17 ± 2 steps and 4.27 ± 0.20 s to load). Additionally, the findings of Chapter 3 revealed that the physical requirements of performing push-starts on different tracks may vary markedly, with substantially higher average step frequency reported on steeper tracks. In fact, skeleton coaches routinely adjust the position of the starting block during dry-land training on the push-track to simulate the different requirements associated with varying track profiles. Importantly, the influence of such block position modifications (to emulate different track profiles) on the development of sled velocity across the start phase and overall start performance remains to be established.

The aims of this study were, therefore, to investigate the effect of altering pre-load distance and track profile on start performance and to assess whether the sled acceleration index could be enhanced by experimentally modifying the distance at which an athlete loads the sled.

7.6. Methods

The push-track data collection sessions for this part of the study were split into two categories to assess the separate effects of altering the block position and loading distance on skeleton start performance. The sled velocity data collection and processing methods closely followed those presented in section 7.2.

7.6.1. Altering block position

The same 13 skeleton athletes who participated in the first part of this chapter were also involved in this section of the study. Data collection sessions formed part of a longitudinal two-day monitoring protocol in which a battery of physical tests was conducted (described in detail in Chapter 4). At each testing session, participants performed three maximal effort push-starts from both block positions (standard and backward; Figure 7.6). In the backward trials, the block was moved 2.5 m backward to mimic a longer starting profile (i.e. the brow was 2.5 m further from the block than during standard block trials).

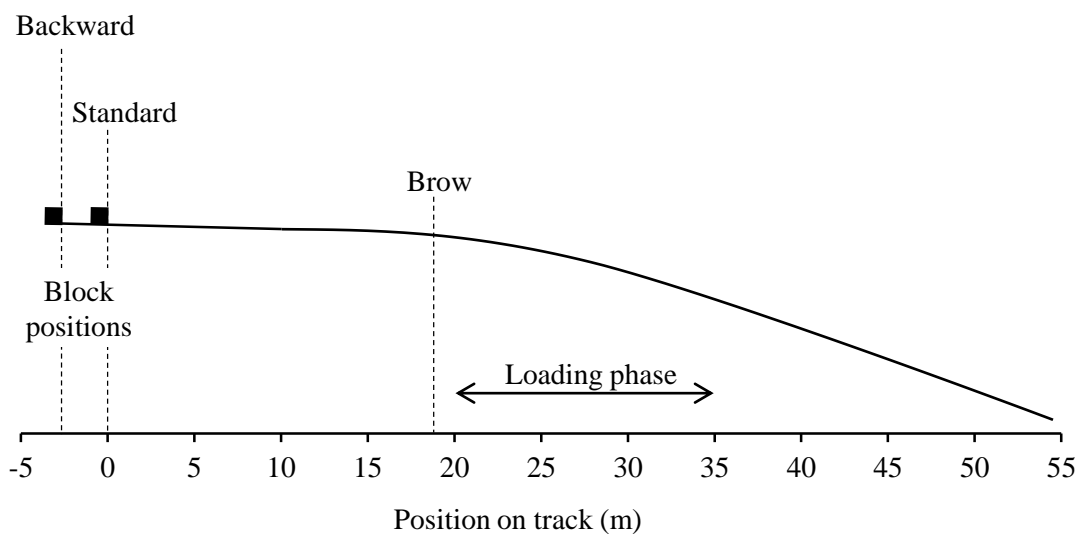


Figure 7.6. Schematic representation of the push-track set-up with the two different block positions.

7.6.2. Altering loading distance

Ten (5 elite squad and 5 talent squad) skeleton athletes were included in this section of the study. Data collection sessions took place weekly (between 0930 and 1130 hours)

across a six week period of summer training, with athletes attending an average of three data collection sessions. At each testing session, participants performed a total of six maximal effort push-starts from the standard block position, two in each condition (preferred, long and short distance push-starts). The conditions related to how far athletes perceived they were running before loading the sled. Athletes were simply instructed to under-run and over-run their preferred distance in the short and long conditions, respectively. Following a competition warm-up, athletes performed two preferred distance push-starts at each testing session to provide a standard reference with which long and short pushes were compared. The ordering of the remaining conditions was randomised to avoid sequencing effects.

7.6.3. Statistical analysis

Means and standard deviations were calculated for each of the following start performance descriptors for each athlete in each condition (short, long, preferred loading distance and from standard and backward block position): number of steps, pre-load velocity, pre-load distance, velocity drop and load effectiveness. Effect sizes (Cohen, 1988) were used to assess for differences in all start performance descriptors between the three loading conditions (preferred, short and long). The within-athlete relationships between pre-load conditions (velocity and distance) and loading variables (velocity drop and load effectiveness) were assessed using Pearson correlation coefficients. Individual coefficients were combined via Fisher transformation using an online spreadsheet (Hopkins, 2006b) to provide the group mean correlation coefficients (\pm 90% CI) and magnitude-based inferences.

Effect sizes were also calculated to assess the effect of differing loading strategies on overall start performance (the sled acceleration index) for individual athletes. Sample size estimation for effect size analysis was conducted using a published spreadsheet (Hopkins, 2006c), which revealed that a minimum sample size of 5 trials per athlete, per condition was required to achieve adequate precision. This relates to a 5% chance of type I and type II errors, as recommended for this type of analysis (Hopkins, 2006a). An insufficient number of trials were available for two elite and one talent squad athlete(s) and so the altering loading distance part of this study was possible for seven (3 elite and 4 talent squad) athletes only. Additionally, effect sizes were used to assess for differences in start performance between the two track profiles (push-starts from the

standard and backward block position). Variables of interest included number of steps taken before loading, pre-load velocity, pre-load distance (and track position) and mean sled velocities (every 2.5 m of the track up to the 25 m mark). The magnitudes of the effect sizes and correlation coefficients were interpreted in exactly the same way as previous chapters (see section 3.2.4 in Chapter 3 for full details).

7.7. Results

7.7.1. The effect of altering loading distance on start performance

Group mean (\pm SD) values for all start performance descriptors in the three loading conditions and the associated magnitude based inferences, are provided in Table 7.3.

Table 7.3. Start performance descriptors (mean \pm SD) in three loading conditions.

	Loading condition			Magnitude based inference
	Short	Preferred	Long	
Number of steps	14.4 \pm 1.2	15.9 \pm 1.2	17.4 \pm 1.3	P > S L > P L > S
Pre-load velocity (m·s ⁻¹)	7.74 \pm 0.68	8.15 \pm 0.62	8.53 \pm 0.65	P > S L > P L > S
Pre-load distance (m)	23.18 \pm 2.19	25.63 \pm 1.76	28.60 \pm 2.68	P > S L > P L > S
Velocity drop (m·s ⁻¹)	0.24 \pm 0.15	0.36 \pm 0.19	0.41 \pm 0.19	P > S L > S
Load effectiveness (m·s ⁻¹)	0.66 \pm 0.22	0.55 \pm 0.18	0.39 \pm 0.17	S > P P > L S > L
Sled acceleration index	2.56 \pm 0.21	2.59 \pm 0.22	2.58 \pm 0.21	

> denotes a value is substantial greater than the other. S, P, L denote short, preferred and long conditions, respectively

Number of steps, pre-load velocity and pre-load distance were all substantially higher in the long vs. preferred condition (effect size \pm 90% CI = 1.26 \pm 0.37, 0.60 \pm 0.18 and 1.34 \pm 0.39, respectively) and in the preferred vs. short condition (effect size = 1.25 \pm

0.36, 0.64 ± 0.19 and 1.24 ± 0.36 , respectively). For example, when athletes increased the pre-load distance by 2.97 m by taking 1.5 more steps (on average from the preferred to long condition), pre-load velocity was also found to be $0.37 \text{ m}\cdot\text{s}^{-1}$ higher. However, velocity drop was also substantially greater during both the long and preferred, compared with the short, distance pushes (effect size \pm 90% CI = 0.99 ± 0.43 and 0.66 ± 0.26 , respectively). Additionally, substantially more effective loading phases were reported in the short vs. preferred (effect size \pm 90% CI = 0.53 ± 0.26), preferred vs. long (effect size = 0.95 ± 0.13) and the short vs. long (effect size = 1.36 ± 0.18) conditions. Thus, when pre-load velocity increased by $0.37 \text{ m}\cdot\text{s}^{-1}$ with the ~ 3 m increase in loading distance (longer vs. preferred distance pushes), the effectiveness of the loading phase was found to be $0.16 \text{ m}\cdot\text{s}^{-1}$ lower. However, no overall differences in start performance (the sled acceleration index) between the three loading distance conditions were observed at a group level (effect sizes \pm 90% CI ranged from -0.17 ± 0.07 to -0.09 ± 0.09).

The within-athlete correlations between several of these start performance descriptors are provided in Figure 7.7. Each of the six combined correlation coefficients were found to be clear relationships. For all 10 athletes, pre-load distances were positively related to higher pre-load velocity ($r = 0.94$, 90% CI = 0.92 to 0.96). However, higher pre-load distances were also associated with lower load effectiveness ($r = -0.75$, 90% CI = -0.81 to -0.68) and a similar negative relationship was observed between pre-load velocity and load effectiveness ($r = -0.87$, -0.90 to -0.83). Similarly, positive relationships were found between velocity drop and both pre-load velocity ($r = 0.52$, 90% CI = 0.40 to 0.62) and pre-load distance ($r = 0.35$, 0.21 to 0.47), and a greater velocity drop was associated with lower load effectiveness ($r = -0.55$, -0.64 to -0.43).

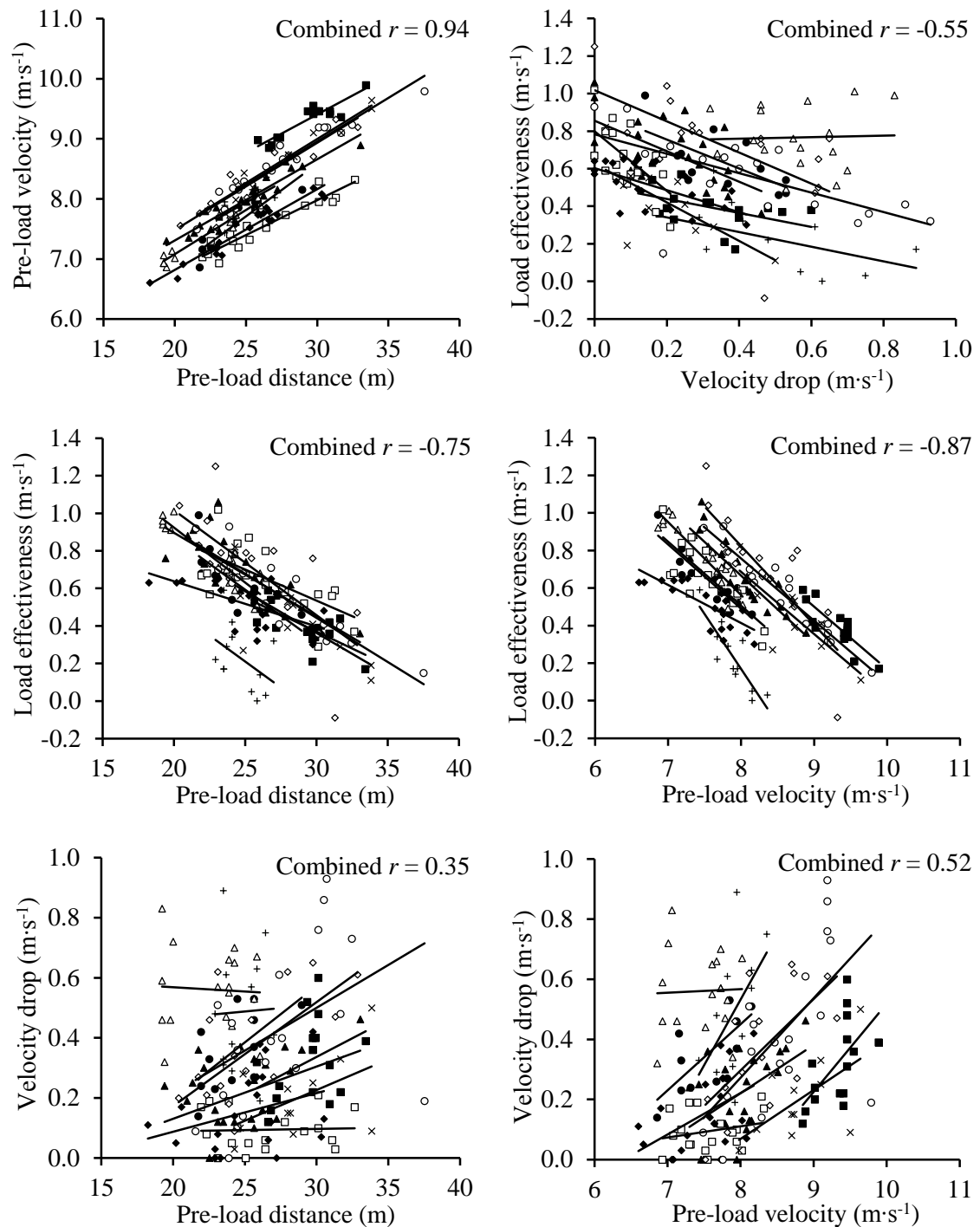


Figure 7.7. Within-athlete relationships between pre-load velocity, pre-load distance, load effectiveness and velocity drop ($n = 10$) and combined correlation coefficients (all 10 individual athletes' correlation coefficients combined). Each symbol represents an individual athlete and linear trendlines represent within-athlete correlations.

The mean sled acceleration indices achieved by individual athletes in the three different conditions are provided in Table 7.4.

Table 7.4. Sled acceleration indices (mean \pm SD) achieved by seven individual athletes in the three loading conditions.

	Loading condition		
	Short	Preferred	Long
Athlete E1	2.47 \pm 0.06	2.49 \pm 0.06	2.46 \pm 0.08
Athlete E2	2.28 \pm 0.04	2.35 \pm 0.03	2.33 \pm 0.03
Athlete E3	2.92 \pm 0.02	2.95 \pm 0.02	2.92 \pm 0.03
Athlete T1	2.57 \pm 0.05	2.54 \pm 0.04	2.59 \pm 0.06
Athlete T2	2.66 \pm 0.07	2.72 \pm 0.05	2.70 \pm 0.05
Athlete T3	2.65 \pm 0.03	2.73 \pm 0.09	2.74 \pm 0.02
Athlete T4	2.28 \pm 0.05	2.30 \pm 0.03	2.26 \pm 0.05

N.B. Athletes E1, E2 and E3 denote elite squad athletes. Athletes T1, T2, T3 and T4 denote talent squad athletes.

The individual effects of adopting differing loading strategies are illustrated in Figure 7.8. All three elite squad athletes were found to perform better in the preferred distance pushes, compared with those in the short condition (effect sizes \pm 90% CI ranged from 0.35 \pm 0.40 to 2.13 \pm 1.2). For two of these elite athletes, preferred distance pushes were also superior to those in the long condition (effect sizes \pm 90% CI = 0.88 \pm 0.66 and 1.47 \pm 1.30 for E2 and E3, respectively). Athlete E2 also exhibited a substantially higher sled acceleration index in the long vs. short condition (effect size \pm 90% CI = 1.55 \pm 0.75). While elite athletes performed best in the preferred condition, long and short conditions sometimes had favourable start performance outcomes for talent squad athletes. For example, athlete T1 performed a substantially better start phase in the long vs. preferred loading distance condition (effect size \pm 90% CI = 0.87 \pm 1.03). Additionally, running further (rather than loading at a short distance) seemed to be beneficial for athletes T2 and T3, with a substantially higher sled acceleration index in the long vs. short conditions (effect sizes \pm 90% CI = 0.72 \pm 0.78 and 1.57 \pm 1.24, respectively) and in the preferred vs. short conditions for the same athletes (effect sizes = 0.98 \pm 0.80 and 1.32 \pm 0.90, respectively). On the other hand, short distance pushes resulted in superior start performance compared with the long distance pushes for athlete T4 (effect size \pm 90% CI = 0.35 \pm 0.45).

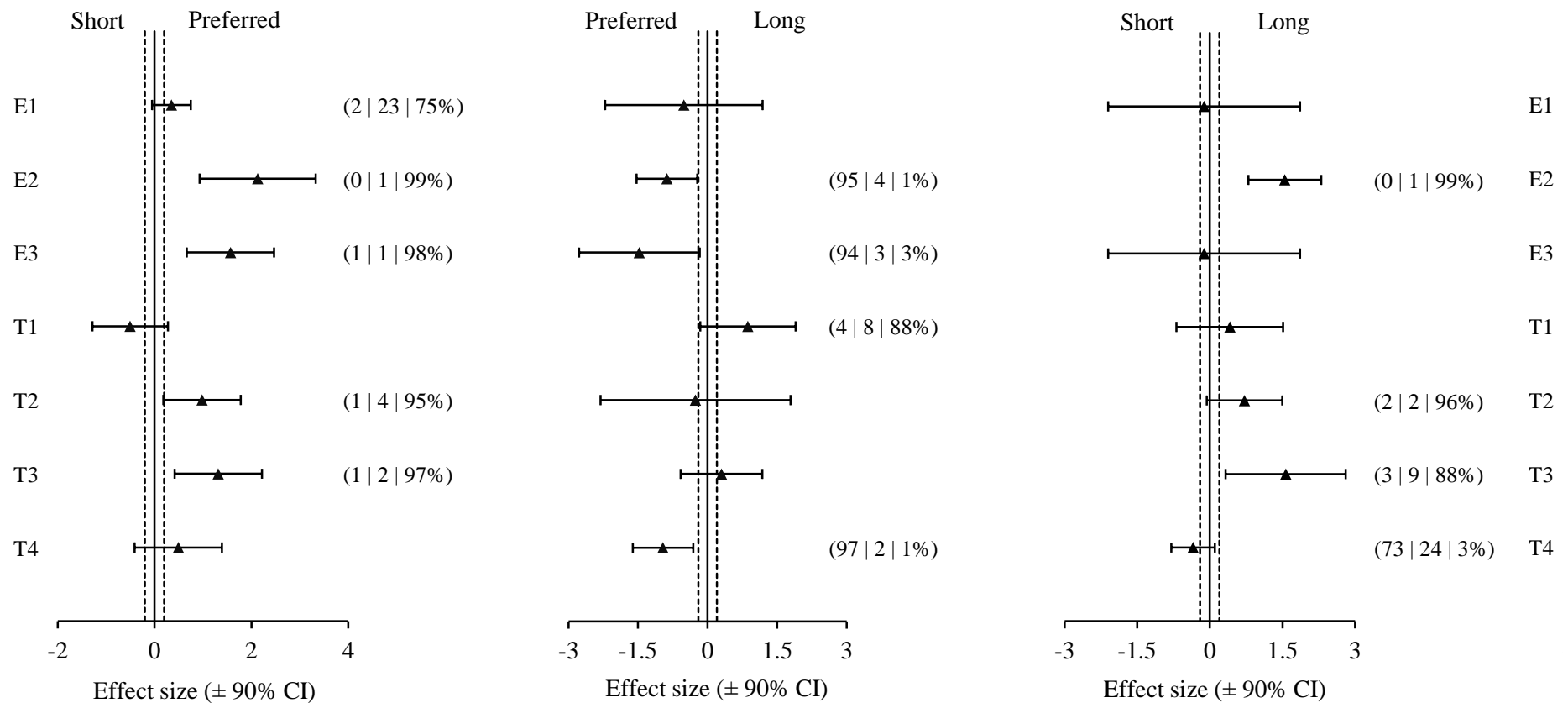


Figure 7.8. Differences (effect size \pm 90% CI) in start performance between three loading conditions for individual athletes ($n = 7$).

E data labels denote elite squad athlete. T data labels denote talent squad athlete. Bars represent 90% confidence intervals.

Central area (0.0 ± 0.2) indicates a trivial effect. Percentages in brackets (presented only when a substantial effect is detected) represent the likelihoods that the effect (right vs. left condition) is negative | trivial | positive.

7.7.2. Start performance descriptors from two different block positions

A comparison between the start performance descriptors for the two block positions are presented in Table 7.5. When starting from the backward block position, in comparison with the standard block position, participants took substantially more steps and loaded at a substantially greater distance from the block (effect sizes \pm 90% CI = 0.86 ± 0.27 and 1.04 ± 0.33 , respectively). However, the absolute pre-load track position (the position of the sled on the track relative to the standard block position) was not different between conditions (effect size \pm 90% CI = -0.08 ± 0.23). There was also no effect of block position on 15 m velocity and pre-load velocity between the block positions (effect sizes \pm 90% CI = 0.04 ± 0.01 and 0.08 ± 0.13 , respectively). Additionally, the loading phase appeared to be performed in a comparable way across conditions with trivial effects found for velocity drop and load effectiveness (effect sizes \pm 90% CI = -0.01 ± 0.29 and -0.04 ± 0.27 , respectively).

Table 7.5. Start performance comparison between two block positions.

Start performance descriptor	Standard block position (mean \pm SD)	Backward block position (mean \pm SD)	Percentage likelihoods
Number of steps	16.2 \pm 1.2	17.3 \pm 1.5*	0 0 100%
Pre-load distance from the block (m)	26.51 \pm 1.93	28.83 \pm 2.55*	0 0 100%
Pre-load absolute track position (m)	26.51 \pm 1.93	26.33 \pm 2.55	19 78 3%
Pre-load velocity (m·s ⁻¹)	8.37 \pm 0.58	8.42 \pm 0.62	0 93 7%
Velocity drop (m·s ⁻¹)	0.36 \pm 0.20	0.36 \pm 0.15	14 75 11%
Load effectiveness (m·s ⁻¹)	0.51 \pm 0.17	0.50 \pm 0.15	15 78 7%
Velocity 15 m from block (m·s ⁻¹)	7.01 \pm 0.36	7.00 \pm 0.35	0 100 0%

* denotes value is substantially greater from backward compared with the standard block position. Percentage likelihoods represent the likelihood that the effect is negative | trivial | positive. N.B. ‘absolute track position’ refers to the position of the sled on the track relative to the standard block.

To better understand the above similarities and differences in start performance between the different track profiles (Table 7.5), the velocity profiles of the sled from the two block positions were further investigated. At absolute track positions from the 0 to 20 m marks, sled velocity was found to be substantially higher in the backward block position trials compared with those from the standard block position (Figure 7.9). However, from the 22.5 m track position onwards, sled velocities were similar (trivial effect) between the two block positions.

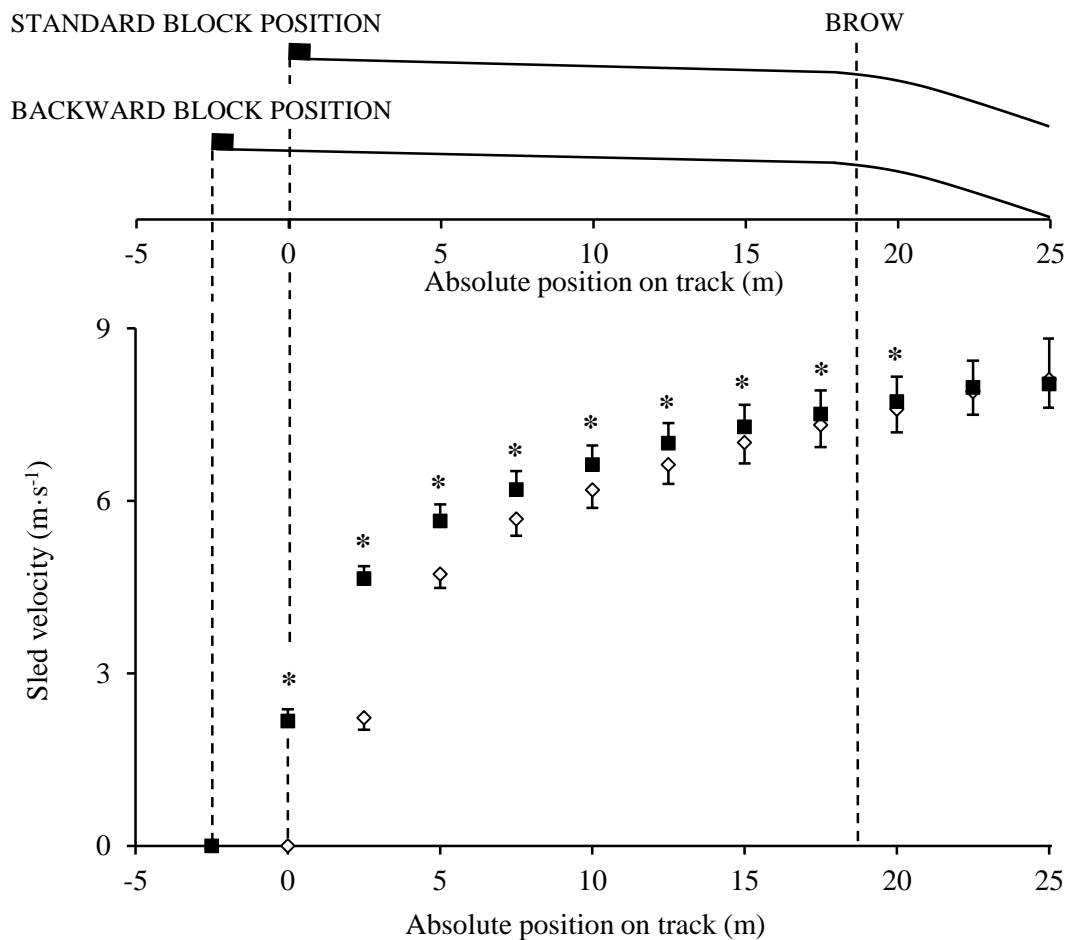


Figure 7.9. Approximate track profile (top) and average sled velocity (bottom) from the block to the 25 m position on the track for all athletes starting from two block positions. Solid squares denote sled velocity from the backward block position. Empty diamonds denote sled velocity from the standard block position. * denotes substantially greater sled velocity from the backward compared with the standard block position.

7.8. Discussion

The purpose of this study was to assess the influence of altering track profile and loading distance on start performance. A key finding was that higher pre-load distances were associated with higher pre-load velocities. However, there appeared to be a trade-off between pre-load velocity and the success of the loading phase. An additional finding was that skeleton athletes take a greater number of steps on flatter track profiles, however, the absolute track position and velocity of the sled at the pre-load time point were not different when performing on two different track profiles.

Skeleton athletes were found to attain higher pre-load velocities when loading distance was increased beyond the preferred position (Table 7.3 and Figure 7.7). In part I of this study, pre-load conditions (distance and velocity) and the loading phase independently contributed to the start phase. However, it is likely that in reality, a change in the pre-load conditions may influence the subsequent loading phase. Indeed, higher pre-load velocities and thus, higher pre-load distances were associated with a greater velocity drop (combined $r \pm 90\%$ CI = 0.52 and 0.35, respectively) and a less effective loading phase (combined $r \pm 90\%$ CI = -0.87 and -0.75, respectively) in this study. For example, when athlete T1 increased pre-load velocity from 7.94 to 8.38 m·s⁻¹ (when loading distance was increased from 24.6 to 27.6 m in the long compared with preferred condition), the velocity drop during the load increased (from 0.21 to 0.29 m·s⁻¹) and the effectiveness of the loading phase decreased (from 0.69 to 0.54 m·s⁻¹). Thus, this study has revealed a potential trade-off between how far athletes push before loading the sled and the success of the loading phase challenging the notion that athletes should simply maximise pre-load velocity. Given this trade-off and the possible manipulation of start performance descriptors through altering loading distance (Table 7.3), an important step was to assess whether individual athletes' start performances can be enhanced by adapting pre-load conditions.

The optimum loading distance (short, preferred, long) was found to differ amongst the group of skeleton athletes involved in this study. For all three elite squad and two talent squad (T2 and T3) athletes, it was clear that the short loading distance intervention was not favourable and superior start performances occurred when athletes ran to their perceived optimum distance before loading (Figure 7.8). For example, the sled acceleration index achieved by athlete T3 during normal distance pushes was 2.73

compared with 2.65 during shorter distance pushes. For two of the elite squad athletes (E2 and E3), preferred loading distance push-starts were also found to be more effective than longer distance push-starts. The perception of optimum loading distance, therefore, appears to be accurate in these more experienced athletes and this may reflect a refinement of loading distance across the large number of push-starts accumulated by the elite squad athletes. On the other hand, this could demonstrate that after training in a certain way (preferred loading distance) for a large number of runs, any deviation from the norm is more likely to be unfavourable for elite athletes simply because they are less accustomed to the long and short (compared with the preferred) loading distance conditions. This highlights an important consideration when evaluating the efficacy of interventions in elite athletes. This is, however, a difficult issue to overcome in this setting because elite athletes have, by definition, fine-tuned their performances to an exceptional degree. A potential solution could be to integrate the intervention conditions within training for a period of time before any testing. However, such control over training can be challenging in the applied setting (Kearney, 1999) and was beyond the scope of the current study.

Superior performances were sometimes exhibited in one of the intervention conditions for the talent squad athletes. This is perhaps reflecting the relatively fewer number of push-starts performed by talent squad athletes and therefore, less skill refinement may have occurred. Only one athlete (T4) benefitted from loading earlier rather than later (short vs. long conditions; sled acceleration index was 2.28 vs. 2.26, respectively). For this individual, it appears that the higher pre-load velocities associated with longer pushes (8.07 vs. $7.20 \text{ m}\cdot\text{s}^{-1}$; long vs. short, respectively) is outweighed by the negative effect that over-running has on the effectiveness of the loading phase (0.48 vs. $0.73 \text{ m}\cdot\text{s}^{-1}$; respectively), as shown in Figure 7.7. However, the sled acceleration index was found to be higher in the long (compared with the preferred; 2.59 vs. 2.56 , respectively) distance condition for one talent squad athlete (T1), despite the associated reduction in load effectiveness (0.69 vs. $0.54 \text{ m}\cdot\text{s}^{-1}$, respectively). Thus, it may be that this individual is better able to preserve loading phase performance when transitioning from the preferred to long condition than the other athletes.

Athletes were shown to alter the number of steps they take before loading when performing a push-start on different track profiles with a greater number of steps taken

on the flatter profile (backward block position; mean \pm SD = 17.3 ± 1.5 steps) compared with the standard profile (16.2 ± 1.2 steps). Similar adjustments have been reported previously on ice-tracks of varying profiles (Bullock et al., 2008 and Chapter 3). As a consequence, pre-load distance (relative to the block) was found to be greater on the longer profile compared with standard profile (28.8 ± 2.6 vs. 26.5 ± 1.9 m; mean \pm SD). Interestingly, the absolute position of the load and pre-load velocity were similar between conditions (mean \pm SD = 26.5 ± 1.9 m and 8.37 ± 0.58 m·s⁻¹ vs. 26.3 ± 2.6 m and 8.42 ± 0.62 for standard and backward block positions, respectively). Therefore, the additional steps taken and total distance sprinted did not seem to translate to greater velocity at the pre-load time point. This may be surprising given the positive associations reported here between pre-load distance and velocity (Figure 7.7; standard block position) and those between the number of steps taken and start time documented previously (Bullock et al., 2008).

In order to understand the above observations further, a closer examination of the sled velocity profile was necessary. When considered at absolute track positions, it became apparent that sled velocities were substantially higher in the backward (vs. standard) block condition until the 20 m track position (i.e. before the brow, when the gradient is approximately 2%). However, following this track position (when the track gradient becomes steeper following the brow), athletes quickly attained similar velocities from both block positions (Figure 7.9). The higher sled velocities associated with the backward block conditions have therefore diminished by the loading phase perhaps indicating that an athlete is approaching their maximum capabilities. However, it was previously shown in this study that athletes were able to attain higher velocities when deliberately over-running (i.e. during long distance pushes; Table 7.3). Therefore, the observed effect is unlikely to be related to physical limitations. An alternative explanation could be that athletes modulate sled velocity in order to protect their pushing technique on the steeper sections of the track, enabling them to load the sled more effectively. Indeed, load effectiveness and the velocity drop during the load were similar across block positions (Table 7.5). Future work is needed to investigate the effect of more extreme profile alterations on the sled velocity profile. Additionally, if instrumentation of ice-track sleds is possible, potentially valuable insight could be gained regarding the effect of differing profiles on the velocity of ice-track sleds across the start phase.

7.8.1. Conclusion

Longer loading distances were associated with higher pre-load velocities but less effective loading phases. Thus, a trade-off emerged between attaining high sled velocities and performing a successful load. This warrants consideration when attempting to optimise start performance by altering loading distance. Importantly, maximising pre-load velocity does not always appear to be the most favourable strategy. Perceptions of the optimum loading distance were found to be accurate in the more experienced elite squad athletes, who appear to have fine-tuned their performances on the dry-land push-track. However, simply modifying the distance of the loading phase could lead to performance enhancement for less experienced athletes. Thus, the inclusion of this testing appears to be worthwhile especially in young, developing skeleton athletes. As the number of steps taken are known to vary markedly across different tracks (Bullock et al., 2008), along with the associated physical requirements (Chapter 3), more work is required to understand whether start performance on different track profiles could be improved by altering the loading distance adopted by athletes across both squads. Finally, when performing starts on flatter profiles, it seems important to ensure that any additional ground contact phases do, in fact, positively contribute to performance. This has important practical implications for skeleton coaches attempting to enhance performance across tracks with differing track profiles.

7.9. Chapter summary

This chapter has outlined a novel method to analyse the start phase in more detail than was previously possible and has uncovered additional factors which determine start performance. In part I, the sled acceleration index was developed to differentiate the success of the start phase and several performance determining aspects of the sled velocity profile were identified. In part II, experimental interventions demonstrated the effect of altering track profile on the sled velocity profile and revealed an interaction between pre-load velocity and load effectiveness which is crucial to take into consideration when coaching athletes to load at different distances and/or on different tracks. Some athletes clearly benefitted from adapting the distance of the loading phase and thus, this testing appears to have an important role when attempting to enhance start performance, particularly for developing skeleton athletes. Overall, the continuous sled velocity measurement appears to provide a tool with which to not only increase the understanding of this phase, but also to ultimately enhance skeleton start performance.

CHAPTER 8: GENERAL DISCUSSION

8.1. Introduction

The general consensus appears to be that a gap exists between sport and exercise research and applied practice (Knudson, 2005; Amonette et al., 2010) and it is typically perceived by coaches that scientific findings seldom translate to performance enhancement (Martindale and Nash, 2013). An applied research model for the sport sciences (ARMSS) has been developed (Bishop, 2008) in an attempt to overcome this disparity and direct the research process towards the issues which are most pertinent to the performance in question. The framework of this multi-staged model (fully outlined in Chapter 2; Figure 2.1) is reflected in the progression of the investigations conducted throughout this thesis, with the intention to maximise the impact of this work on skeleton start performance.

From the inception of the research process, a clear definition of the problem must be obtained by thoroughly evaluating the strength of the literature. This must form the first stage of the ARMSS (Bishop, 2008), because in the absence of this knowledge base, subsequent studies are likely to be misconceived. Thus, in Chapter 2, the current understanding surrounding the skeleton start was evaluated. Although it was demonstrated that the start phase is amongst the success determining factors in skeleton, a paucity of knowledge regarding the contributing factors to performance was clear and there was a clear opportunity to advance the knowledge surrounding the skeleton start.

The aim of this thesis was, therefore, to increase the understanding of the underlying determinants of skeleton start performance in order to inform and enhance training practices. A series of six research questions were posed in Chapter 1 in order to address this overall aim. Accordingly, these research questions directed the investigations presented in Chapters 3 to 7. The following section addresses each of these questions separately and the main findings of this thesis are summarised. The subsequent section includes an overall discussion of this work and the practical implications which have emerged from this thesis. This chapter then evaluates the impact of this work on start performance and the methodological principles adopted throughout these investigations are discussed. Finally, potential areas of future study are proposed.

8.2. Addressing the research questions

The following section will outline the key findings which address each of the six research questions which were initially posed in section 1.3 of Chapter 1.

i. How do skeleton athletes perform the start phase on different tracks and are dry-land push-starts comparable with those on ice-tracks?

There was marked between-athlete variation in all start technique descriptors, however, athletes performed comparably on the dry-land push-track and the two ice-tracks. Dry-land push-start velocities were more closely associated with ice-track start velocity at Winterberg ($r = 0.96$), where a fast start is considered to be more crucial to success, than at Altenberg ($r = 0.82$). The main differences between tracks related to the number of steps taken before loading and average step frequency with a fewer number of steps but higher step frequency exhibited on steeper tracks.

ii. What are the key physical characteristics underlying skeleton start performance?

Principal component analysis revealed three factors amongst a battery of physical test scores relating to sprint ability, lower limb power and strength-power characteristics. Each of these factors significantly contributed to the prediction of start performance ($R^2 = 0.86$), with sprint ability (unresisted 15 m sprint time) identified as the main contributing factor to ($R^2 = 0.81$).

iii. What are the biochemical responses to physical exercises and does testosterone influence performance and lean mass accrual?

Serum testosterone was the only hormone to be substantially elevated in response to push-track tests, however, there was only a trivial response to vertical jump tests. Baseline serum testosterone was positively related to sled velocity within-athletes ($r = 0.28$, 90% CI = 0.02 to 0.50). Additionally, maintaining an elevated testosterone concentration and testosterone responsiveness (above baseline) across a training season appeared important for lean mass accrual ($r = 0.81$ and 0.66, respectively).

iv. Can dual-energy X-ray absorptiometry detect true body composition changes in trained athletes and what are the performance implications of these changes?

Many ‘true’ body composition changes were detected across the training seasons, which were seemingly in line with the training emphases (for example, lean mass gains across hypertrophy-based training blocks). Changes in body composition had important performance implications with increases in lean mass associated with increases in power ($r = 0.53$), whereas fat mass accumulation was detrimental to physical performance ($r = -0.44$).

v. Which aspects of the sled velocity profile are associated with superior skeleton start performance?

Multiple regression revealed four start performance descriptors (pre-load velocity, pre-load distance, load effectiveness and velocity drop) to significantly contribute to the prediction of the sled acceleration index ($R^2 = 0.99$). Pre-load velocity and load effectiveness were positively associated with the sled acceleration index, whereas pre-load distance and velocity drop both negatively contributed to start performance.

vi. How do alterations to loading distance and track profile influence sled velocity and can modifications to loading distance enhance performance?

Pushing the sled further before loading was strongly associated with higher pre-load velocities ($r = 0.94$). However, higher pre-load velocity and distance were associated with lower load effectiveness ($r = -0.87$ and -0.75 , respectively) and a greater velocity drop during loading ($r = 0.52$ and 0.35 , respectively). There appeared to be some scope to enhance start performance through altering loading distance, particularly in developing athletes. As expected, athletes took more steps and loaded further from the block on the flatter track profile (backward block position). However, absolute track positions were similar (26.5 vs. 26.3 m from the standard block) and no differences in pre-load velocity were detected (8.37 vs. $8.42 \text{ m}\cdot\text{s}^{-1}$).

8.3. Overall discussion and practical implications

Few investigations have explored the contributing factors to a fast skeleton start. Skeleton athletes have previously been shown to differ in the number of steps taken before loading the sled and superior starters tended to take a greater number of steps during ice-track competitions, particularly on tracks where a fast start was important to overall success (Bullock et al., 2008). In Chapter 3, high average step frequency seemed to be important to performance by allowing athletes to run further before loading and to achieve an overall faster start. It was therefore speculated that physical capacity could be an important determinant of the distance an athlete pushed the sled before loading (number of steps taken), as well as start phase success. Thus, it was conceivable that the ability to rapidly apply high relative forces at high velocity was an important physical attribute for skeleton athletes to possess. In fact, the chapter which followed (Chapter 4) identified several lower limb strength-power scores to be positively associated with push performance and higher velocity (lower load) measures emerged as the primary contributors. Following the development of the continuous sled velocity measurement (Sleed; UK Sport, Sheffield Hallam University), it was subsequently shown (in Chapter 7) that these key physical predictors of performance did, in fact, regulate both the velocity and distance at which an athlete loaded. Thus, the links between physical capacity, loading distance and start performance (initially proposed in Chapter 3) were largely confirmed by the findings of these subsequent chapters.

It is therefore encouraged that skeleton coaches endeavour to improve the key physical abilities identified in Chapter 4, to allow athletes to attain higher sled velocities and perform an overall faster start phase. These physical characteristics should now be used to guide training and enhance skeleton athlete development. Of particular importance appears to be sprint ability and the capacity to perform powerful, high velocity muscular efforts. Thus, coaches should prescribe specific training blocks to enhance the physical characteristics identified by this research as success determining factors and use the associated physical tests as benchmarks against which skeleton athlete development can be evaluated and talent identified. In fact, following the finding that sprint ability was the strongest predictor of push performance (Chapter 4), training programmes were adapted to place more emphasis on running based drills and technical work, with the view to enhancing this crucial component and thus, potentially start performance.

Additionally, wider application of the methods presented in Chapter 4 (to identify and validate a set of key physical predictors of performance) to other athletic performances is encouraged. This process not only resulted in a predictive model which can be used to set training targets and model training projections within the sport of skeleton, but also demonstrated a method to empirically evaluate the utility of a battery of physical measures. For example, the principal component analysis stage of this process ensures independent constructs are being measured and the regression analysis can then confirm whether the variables actually contribute to the performance in question. Importantly, such analysis allows the formation of a regression equation which has clear implications for talent identification processes, but can also provide a scientifically validated tool in which to monitor an athlete's training status. These methods can be applied across all sports to obtain a key set of performance predictors and thus, improve the efficiency of athletic testing batteries. The number, nature and predictive power of the independent variables will, naturally, vary greatly depending on the unique requirements of the sport. For example, it seems as though the skeleton start can be considered a largely raw physical endeavour, whereas other sports may include more technical and/or tactical aspects which could have a greater influence on success.

A further important finding to emerge from this work was that, in the absence of physical advancement, interventions to increase pre-load velocity (by deliberately loading later than usual; part II in Chapter 7) do not necessarily result in performance enhancements. This is partly due to the crucial trade-off between pre-load velocity and the effectiveness of the loading phase. In fact, taking a greater number of steps does not always guarantee a higher pre-load velocity, as athletes appeared to modulate sled velocity in order to load the sled more effectively (when track profile was modified in Chapter 7, part II). These findings certainly warrant consideration when attempting to implement interventions to enhance skeleton start performance. Specifically, attention should be paid to ensure that any increase in pre-load distance and velocity elicited by an intervention is not outweighed by the associated detriments to the loading phase and *vice versa*. As the success of the loading phase seems to be independent of physical capacity (Chapter 7, part I), an alternative approach to enhancing start performance could be to undertake loading technique training to minimise the velocity drop and thus, maximise load effectiveness. However, the underlying determinants of a successful load

are yet to be investigated and the scope to improve load effectiveness has not been established.

The effect of physical training on these start performance determinants was beyond the scope of this study, however, the abilities of several monitoring protocols to indicate skeleton athlete development in response to training were evaluated in this thesis. For example, the regression equation formulated in Chapter 4 was shown to provide an accurate reflection of skeleton start ability. Additionally, Chapter 5 provided unique biochemical data from a truly elite training environment and has, therefore, offered interesting insight regarding the role of testosterone in the training process. For example, this chapter revealed evidence for a potential influencing role of testosterone on push performance and lean mass accrual in this population. In opposition to the assumptions of previous studies (Rønnestad et al., 2011; West and Phillips, 2012), changes in testosterone concentration across a training period do seem to occur and were important to capture in this study. This is because longitudinal changes in testosterone were associated with lean mass accrual, whereas concentrations at a single time-point (e.g. baseline) were not (Figure 5.3). Thus, an important practical implication to emerge from this work is that hormonal status should be monitored longitudinally. Specifically, changes in circulating testosterone seem to be more informative, when attempting to assess an athlete's potential to adapt to training, than discrete concentrations. However, at this moment in time, the retrospective nature of the blood analysis methods may limit the impact that hormonal analyses can have in the applied field. More immediate feedback may be required before this type of testing can actually inform the training process in practice, and sport scientists should perhaps explore other approaches. As the most likely mechanisms appear to be related to behavioural mechanisms (Cook and Crewther, 2012; Cook and Beaven, 2013; Cook et al., 2013), alternative non-invasive, less expensive, more time efficient and potentially subjective methods may be favourable. Indeed, in Chapter 5, a subjective muscle soreness assessment tool was found to provide similar insight into the physiological status of athletes as the more invasive analysis of serum CK.

The ability of DXA scans to detect meaningful changes in body composition (a further determinant of start performance identified in Chapter 4) in the applied setting was demonstrated in Chapter 6. The important influence of these physique changes on

performance, clearly emphasises the need for the longitudinal assessment of body composition in this athlete group. This chapter also illustrated an important process which can be adopted to establish the reliability of monitoring protocols and allow longitudinal changes in any measure to be more robustly evaluated. In this case, the typical errors of DXA measurements were quantified before being used to detect whether body composition changes exhibited by skeleton athletes were, in fact, ‘true changes’. This approach allowed typically unfavourable body composition changes (increases in fat mass and decreases in lean mass) to be confidently detected across the competition season, through which training and/or nutritional interventions should now target. It is encouraged that this process is followed in applied practice when assessing any longitudinal changes, as without knowledge of the expected measurement errors it is impossible to make valid conclusions regarding an athlete’s development.

In summary, the main practical recommendations that have emerged from this thesis comprise the inclusion of high velocity, sprint-based exercises in skeleton training with the emphasis on improving lower limb power production under lighter loads. It is also encouraged that the regression equation formed in Chapter 4 is utilised when attempting to identify potentially talented athletes. Additionally, coaches should be aware of the unfavourable body composition changes typically exhibited across the competition season (which seem to be detrimental to physical performance) and attempt to implement training and/or nutritional interventions to limit these effects. Finally, skeleton coaches should be mindful of the negative interaction between pre-load velocity and load effectiveness when attempting to modify an athlete’s start phase in order to potentially enhance start performance.

8.4. Evaluating the impact of the research on ice-track performance

As evidenced in section 8.2, the investigations presented in this thesis constitute six out of the eight research stages of the ARMSS proposed by Bishop (2008) to facilitate the transfer of research into performance-enhancing practice. This primarily covers the ‘description’ and ‘experimentation’ aspects of the ARMSS. Ideally, ‘implementation’ based studies (involving interventions in the real sporting setting) would follow, however, these were certainly beyond the scope of the current work. Nonetheless, given the dearth of scientific evidence within skeleton, the research approach adopted in this

thesis has resulted in a unique base of evidence which can translate to the applied setting and inform performance enhancing practice. In fact, there is evidence to suggest that ice-track start performances of the athletes involved in the current study did actually improve across the course of this project. However, evaluating longitudinal changes in skeleton start performance is perhaps more complex than would be expected. In many sports, the progression of athletes can be evaluated by directly comparing race times. In swimming, for example, competitions take place under reasonably fixed conditions (i.e. race distance and pool length) and environmental variation is typically considered negligible (Trewin et al., 2004). A swimmer's development can, therefore, be easily tracked and performance variability may also be readily characterised (Pyne et al., 2004). Although official start (15-65 m) times are provided during ice-track competitions in skeleton, there are several obstacles to overcome before longitudinal changes in start performance can be assessed. For example, the profiles of different ice-tracks vary considerably, and although start rankings may be similar across certain tracks (Chapter 3), start times are not directly comparable (Bullock et al., 2008). Additionally, environmental variation is believed to have a marked influence on skeleton start performance (Bullock et al., 2009b). In fact, remarkable day-to-day variation (up to 0.4 s) in individual athletes' start times (on the same track) can be observed (FIBT, 2015a) and may be somewhat ascribed to differences in ice and/or weather conditions.

Skeleton coaches may, therefore, decide to use start performance ranking and percentage difference from the fastest start time to evaluate the success of an athlete's start phase. However, such measures are confounded by differences in the abilities of athletes across different races or circuits, and may also be skewed by outliers (e.g. an extraordinarily fast starter). Thus, in order to robustly monitor the progression of skeleton start ability and/or to assess the efficacy of an intervention intended to enhance start performance, such variability in the initial race conditions (environmental factors, track characteristics and the calibre of competitors) must be taken into account. By 'matching' athletes who have competed at the same races on multiple occasions across seasons, these confounding effects can be largely negated (see Appendix for full details regarding this approach). Consequently, it was possible to show that the athletes participating in this study had improved their start phases relative to athletes from other

nations across the three season period across which this study was conducted (seasons 2011/12 to 2013/14; Figure 8.1).

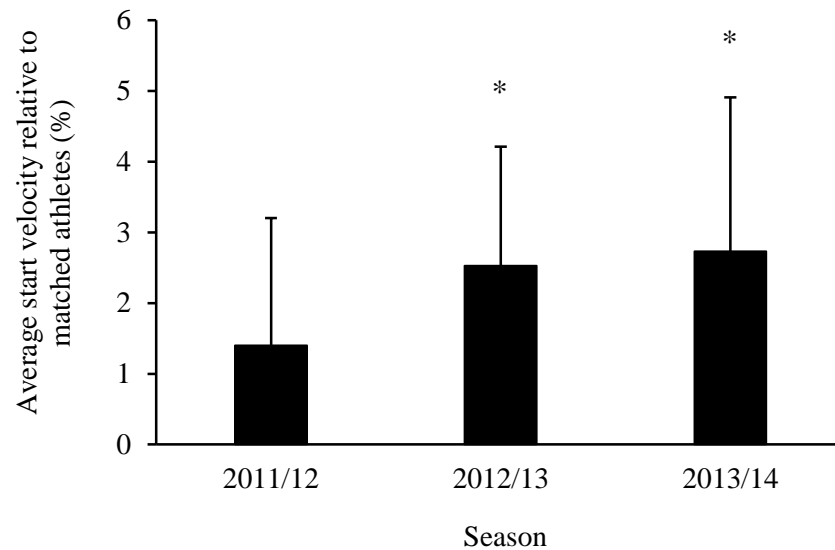


Figure 8.1. Average start velocity difference between seven British skeleton athletes and matched competitors across three competition seasons. Error bars represent standard deviations. * denotes substantially higher than season 2011/12.

In season 2011/12, the seven elite squad skeleton athletes involved in this study were $1.4 \pm 1.8\%$ on average faster than athletes from other nations. As initial training status is considered to regulate adaptation (Kraemer and Ratamess, 2004), the British athletes' improvements between season 2011/12 and season 2012/13 may be even more notable (especially for one athlete, A7; Figure 8.2). At the end of season 2013/14, this margin had substantially increased (effect size $\pm 90\%$ CI = 0.64 ± 0.42) and British athletes were now $2.7 \pm 2.2\%$ ahead (Figure 8.1). Importantly, this does not simply represent the development of the British athletes, but instead reflects the rate of progression above that of the matched competitors. Many nations who compete internationally in skeleton have previously invested in understanding the physical determinants of start performance (USA; Sands et al., 2005) and optimising talent identification and development (Australia; Bullock et al., 2009a). This notwithstanding, the current training processes implemented by British skeleton seem to elicit superior development of start abilities compared with the other nations.

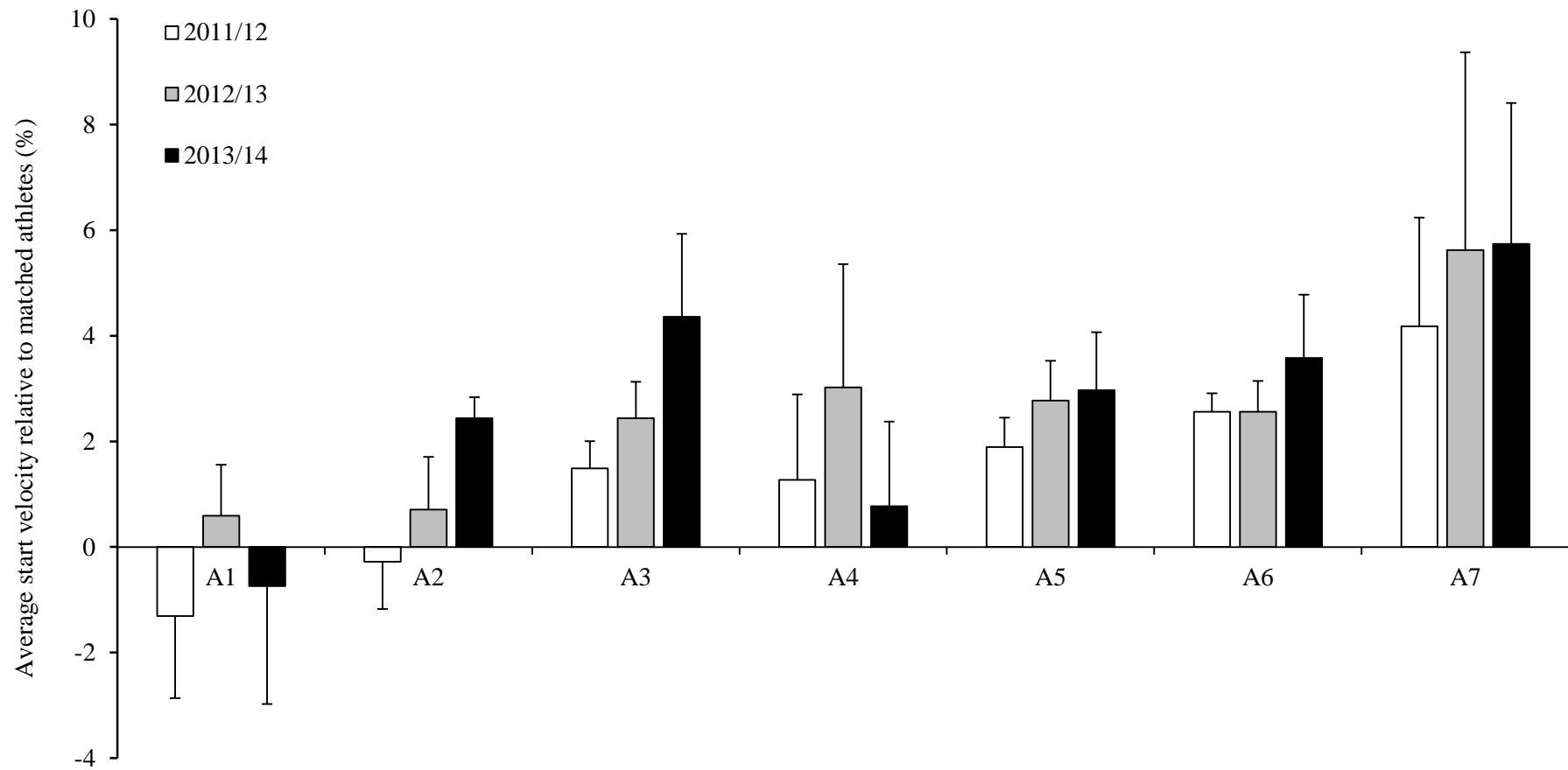


Figure 8.2. Average start velocity difference between each individual British skeleton athlete ($n = 7$) and matched competitors across three competition seasons. Error bars represent standard deviations.

It is impossible to isolate the individual contributing factors to this improvement and in reality, elite sport performance should be considered a complex interaction of multiple components (Smith, 2003). Nonetheless, financial resources (which can support talent development, coaching provision, medical care and scientific research) are considered to be one of the key drivers of international sporting success by providing athletes with more opportunities to train and compete under ideal circumstances (De Bosscher et al., 2009). In fact, out of all Winter Olympic sports, skeleton received the highest funding award from UK Sport across the Olympiad within which this study was conducted, as a result of success in previous Olympic cycles (UK Sport, 2015). It should be noted that this level of funding is still relatively small in comparison with that of summer Olympic sports (for example, UK sport awarded British Cycling over seven times more funding in the lead up to the London Games in 2012; UK Sport, 2015). Even so, it is plausible that this investment, which can supplement many of the aforementioned success-driving factors (including scientific research studies such as those conducted in this thesis) may have influenced the start performance progression observed in this study. Alternatively, it cannot be ruled out that simply increasing the focus on the start phase across this period could have contributed to the observed improvements in start velocity through a psychological phenomenon known as the Hawthorne effect (Brown, 1954).

Although there was an overall improvement at a group level across the three season period ($1.3 \pm 1.2\%$), there was no substantial change between seasons 2012/13 and 2013/14 (Figure 8.1). It is important to note that this does not suggest that British skeleton athletes did not develop their start abilities across this period, but that the change in performance was comparable with that of the matched competitors. This could be explained by an increase in the focus of other nations towards enhancing the start phase in the lead up to the Sochi Olympics (end of season 2013/14). Alternatively, as many of the British skeleton athletes were faster than their fellow competitors in 2012/13, the apparent slowing in athlete progression could also be related to the aforementioned reduced scope for training gains in highly adapted individuals (Kraemer and Ratamess, 2004).

As shown in Figure 8.2, there was a clear positive trend in start velocity relative to matched competitors across the three seasons for five British skeleton athletes. However, two athletes (A1 and A4) did not appear to follow the same progression and

exhibited decreases in their start velocity difference between seasons 2012/13 and 2013/14 (Figure 8.2). It is likely that this discrepancy contributed to the apparent maintenance of the group mean start performance difference across these seasons. It may be noteworthy that the athletes who seemed to diverge from the group trend (A1 and A4) were the only athletes who did not train full time at the central base of British skeleton for the entire three year period. Thus, it is conceivable that these athletes would have had reduced access to resources (e.g. facilities, coaches, sports science support and research) and may have performed fewer push-starts on the dry-land push-track across the summer training season compared with the other team members. Potentially, this may have limited the degree to which these athletes developed their physical capabilities and refined their pushing technique. Nonetheless, by adopting this 'matching' method, it was possible to show that British skeleton athletes' start performances in international competitions progressed at an overall faster rate than competitors from other nations, across the three seasons which culminated with the Sochi Olympics (2011/12 to 2013/14). Although it is not possible to elucidate the exact contributing factors to this improvement, it is plausible that the considerable investment in resources (such as facilities, coaching staff and scientific research projects) may have played an important role.

8.5. Discussion of the methodological principles

It is notoriously difficult to collect scientific data in a truly elite training environment (such as that of the current work) and requires well-controlled methods alongside careful planning and scheduling (Newton et al., 2011). Throughout this thesis, efforts were made to control for potentially confounding variables and ensure that the protocols adopted were both valid and reliable. For example, warm-ups, rest periods and session timings were standardised across the entire testing period and many of the measurement techniques adopted have been shown to have good reproducibility. For example, excellent test-retest reliability has been reported for vertical jump (Goodwin et al., 1999) and sprint (Moir et al., 2004) performance measures collected in a very similar manner to this study. Nonetheless, it is acknowledged that some level of measurement error is inevitable, particularly in the applied sport setting. Thus, multiple trials were conducted where possible and means were calculated to control for this measurement variability. In some cases, the recommended level of control over a protocol was not

possible in this setting. For example, when estimating body composition using DXA in the current work, the stringent scanning protocol advocated by Nana et al. (2012, 2013) was unachievable. To overcome this, Chapter 6 firstly established the level of reliability of the DXA-estimates which can be expected in this context and subsequently used a conservative threshold (double the typical error of the measurement) to evaluate longitudinal changes in body composition. Extensive attempts were therefore made throughout this thesis to ensure that the data collected and the inferences made were as robust as possible. The following sections will further discuss the approach taken throughout this thesis to overcome the challenges faced when analysing data collected in this setting.

8.5.1. Overcoming inevitably small sample sizes

As highlighted by Kearney (1999) difficulties surrounding small sample size are largely unavoidable and ‘appropriate’ statistical power is seldom achieved in performance sport science. By the very definition, elite athletes include a small number of exceptional individuals who differ greatly from novice performers. Thus, in order to address the specific research questions regarding the underlying determinants of elite skeleton start performance, this work had to be based on a small cohort of athletes. Researchers in this field should, of course, be mindful of the implications of inherently low powered studies in both the design and data interpretation stages of their work. Throughout this thesis, several methodological approaches were adopted to specifically overcome this issue.

In Chapter 4, clear relationships were observed between push performance and over 30 physical variables. It was desirable to then identify the primary predictors of skeleton start performance through multiple regression analysis. However, this analysis would require at least five observations for every independent variable (Hair et al., 2009) and such sample sizes were clearly unattainable in this context. Thus, principal component analysis (PCA) was used initially to reduce this large number of predictor variables to a small set of independent factors. Following this reduction, multiple regression analyses was then conducted to investigate the predictive power of each of these independent factors with sufficient statistical power.

It is, however, acknowledged that certain threats to the robustness of this process remained as data from multiple time points from the same athlete were entered into the

predictive analyses (in Chapter 4 and part I of Chapter 7). The use of pooled (and therefore related) data in a multiple regression analysis could result in an overly optimistic model with artificially high R^2 values due to clustering of data points or correlations between residuals. However, it is not possible in this setting to obtain a sufficient number of independent data sets. The methods presented in this thesis are therefore a necessary compromise and were considered justified as long as the limitations were recognised and tested thoroughly. Accordingly, the Durbin-Watson statistic alongside homoscedasticity and normality tests were used to confirm that the data sets in question were appropriate for this analysis (Field, 2000).

Further challenges arose when attempting to cross-validate the model formulated in Chapter 4. Initially, physical test scores from the following training season (2013) were used as the validation data set and the model appeared to provide a stable prediction of start performance ability utilising criteria outlined by Kleinbaum et al. (1988). However, a dependency issue was acknowledged due to the same athletes being included in both of the data sets used to train and validate the model. Ideally, an independent data set would be set aside and used to validate the predictive model, however, this is rarely possible in reality and especially difficult within elite sport. To overcome this issue, a novel K -fold cross-validation technique (Hastie et al., 2009) was adopted to maintain independence between training and validation data sets resulting in a more rigorous assessment of model stability.

8.5.2. Group-based and multiple single-subject analyses

Across this series of investigations, both group-based and single-subject study designs have been adopted where statistically appropriate. The initial stages of the research process (primarily observational studies) tended to involve more group-based study designs. For example, mean physical test scores were used to initially identify those associated with faster push-start performance and group mean responses in selected biomarkers were quantified in Chapter 5. Such analyses can identify general trends to provide an initial research base. However, it is acknowledged that such study designs may mask important individual differences (Dixon and Kerwin, 2002; Bates et al., 2004) and multiple single-subject analyses were also conducted to better understand this variation. For example, when assessing the influence of loading distance on start performance, it was important to assess any differences between conditions on an

individual athlete basis. If such methods had not been adopted, the individual differences observed in Chapter 7 would not have been detected and important information would have been missed when answering the second part of research question vi - ‘*can modifications to loading distance enhance performance?*’. A further intermediate method was also adopted in Chapters 5 and 7 involving a hybrid of these two aforementioned approaches. For instance, within-athlete Pearson correlations were combined to assess the relationship between testosterone and performance, and the interactions between the different aspects of the sled velocity profile. In the absence of this approach, the trade-off between pre-load velocity and load effectiveness may not have been identified, the significance of which became clear in the latter stages of Chapter 7.

8.5.3. *Magnitude based inferences*

Throughout this thesis, effects and associations have been evaluated using magnitude based inferences rather than the more conventional null hypothesis significance testing. The latter, more traditional approach to inferential statistics requires a null hypothesis (no effect) to be stated before a p value is calculated to test whether this hypothesis should be accepted or rejected (the latter case is commonly referred to as a “statistically significant” effect). There is much evidence for the misconception of p values amongst academic researchers (Oakes, 1986), however, this value should only be considered to represent the probability of obtaining the observed results (or more extreme) results, if the null hypothesis is true. In the field of sport and exercise science, typically the null hypothesis is accepted if $p > 0.05$ and rejected if $p \leq 0.05$ (relating to a 5% chance or less of obtaining the observed results, if there is no effect). Although this threshold for statistical significance is widely accepted, it seems somewhat arbitrary and criticisms of this approach have been summarised succinctly by Rosnow and Rosenthal (1989) with the quote that “surely, God loves the .06 nearly as much as the .05”. This dichotomous approach to making statistical inferences using null hypothesis significance testing has come under further scrutiny in recent times (Batterham and Hopkins, 2006; Cumming, 2012; Winter et al., 2014). This criticism is centred on the fact that null hypothesis significance testing is only capable of indicating whether an effect is, or is not, zero. However, in most (if not all) settings, the more pertinent issue is surely the magnitude of the effect and in sports science research, the practical significance of any change to performance must be of greater interest (Batterham and Hopkins, 2006). Although not a

common concern in sports science, it is possible for overpowered studies to result in 'statistically significant' results with no practical meaning. Conversely, results deemed 'not statistically significant' can be practically very meaningful and the proposed need to reconsider the use of the word 'significant' when interpreting research findings (Winter, 2008) is perhaps justified.

As sample sizes are inherently small in elite sport research, type II errors are perhaps more common in this setting (whereby a practically important effect remains undetected through null hypothesis significance testing). In fact, if the traditional approach to statistical inferences had been adopted in the second part of Chapter 7, the potential to enhance start performance through altering loading distance would have been missed on four occasions (out of a total 13 cases where a difference between conditions was detected using magnitude based inferences). For the above reasons, magnitude based inferences (Batterham and Hopkins, 2006) were made throughout this thesis to assess whether relationships and effects observed were likely to be practically meaningful to athletes and coaches. Confidence intervals were therefore used to express the (un)certainly of estimates by defining the likely range of the true value (Cumming, 2012). This method is not completely distinct from null hypothesis testing, and in fact, exactly the same dichotomous decision can be made. This is because a statistically significant effect is one in which the CIs do not cross zero (Cumming and Finch, 2001). However, by using magnitude based inferences, and taking into account the overlap of the CIs across predetermined boundaries, the likelihoods that the effect is positive, trivial or negative can provide crucial insight regarding the likely performance implications of research findings (Batterham and Hopkins, 2006).

In the applied setting, magnitude based analyses are arguably a more favourable approach to statistical inferences because they provide a coach with comprehensible information to make a better informed decision to (or not to) implement a change. Naturally, an intervention is more likely to be implemented if a large chance of a positive beneficial effect is accompanied by a small chance of it being negative or 'harmful' (< 5% likelihood was chosen as a threshold in this case). For example, in Chapter 7, adopting a long loading distance appeared to be clearly favourable over the preferred condition for athlete T4 because a beneficial effect was 97% likely and a harmful effect was only 1% likely. Thus, clearly a coach would encourage an athlete to

run further before loading in this case. However, the percentage likelihoods also provide coaches with information to make their own balanced judgements when the outcome is not so clear. For example, there was no clear benefit or harm for athlete T1 to load at the shorter compared with the preferred distance and this effect was certainly not statistically significant. However, it was found that the shorter condition was 76% likely to be beneficial to performance and only 6% likely to be detrimental for this athlete (T1). In this case, a coach may make an informed decision that, probabilistically, the shorter loading distance should actually be adopted by this individual athlete.

8.6. Future investigations

The evolution of studies conducted in this thesis was outlined in relation to the applied research model for the sport sciences (ARMSS; Bishop, 2008) in section 8.2. Logical progression through the initial six stages (from eight) of this model was evidenced advancing the knowledge surrounding the relatively unexplored skeleton start in a systematic manner. However, further research questions have emerged from this work and more advanced stages of the ARMSS could be addressed by future studies.

This thesis has shown that athletes who are able to attain higher step frequency (Chapter 3) and exhibit higher lower limb power and sprint ability (Chapter 4) are more likely to push the sled further down the track, attaining higher velocities and performing a faster start. The identification of such physical determinants falls under the third stage of the ARMSS (Bishop, 2008) and these types of studies can highlight important areas for training to be directed towards. Having ascertained the key performance predictors, subsequent studies can advance the understanding further by determining how best to modify them (stage 4 of the ARMSS). For example, understanding the effect of different types of training and periodisation of training blocks on the physical development of skeleton athletes, and the associated effect on pre-load velocity, distance, step frequency and overall performance could better inform training prescription for skeleton athletes.

The physical requirements have been shown to vary across tracks as the number of steps taken before loading and the average step frequency exhibited by athletes was shown to differ (Chapter 3). Thus, an understanding of how training influences start performance

on different track profiles could also inform and enhance the preparation of athletes for competition. For example, if the major championships which take place at the end of every competitive season (Winter Olympic Games or World Championships) were on a particularly steep track, knowledge of the best training methods to enhance start performance on that specific track could increase an athlete's chances of overall success.

These proposed training studies would incorporate stages 4 to 6 of ARMSS depending on the nature of the modifications. Ideally, these should take the form of a randomised control trial, which is certainly a challenging study design to implement in the elite sport setting. The reluctance of athletes and coaches to adapt and/or standardise their practice (Kearney, 1999), along with the ethical considerations involved in assigning athletes to the control condition (McNamee et al., 2007), provide likely explanations for the lack of studies of this nature. An alternative design could be more observational and involve the quantification of training load and evaluation of subsequent adaptation. However, more research is required to establish a universal method to quantify the 'dose' of all types of training (resistance, plyometric and push-track training) with the required level of accuracy (Borresen and Lambert, 2009).

The investigations conducted in part II of Chapter 7 were the most advanced, in terms of ARMSS stages (stages 4 to 6). This controlled intervention study determined the most favourable loading distance for individual skeleton athletes to maximise start performance on the push-track. An important, yet challenging, future direction of skeleton start research could therefore investigate the implementation of this intervention in the real sporting setting (i.e. ice-track start performance). Such a study would cover the eighth (and final) stage of the ARMSS. However, one current barrier to many of the future studies proposed here is the instrumentation of ice-track sleds to obtain sled velocity, which is currently only feasible during ice-track training runs because the specification of sleds during competition is strictly controlled (FIBT, 2010). Although such a study is certainly a long-term prospect, the final stage of the research loop must be considered from the outset to ensure that an enhancement in performance is actually achievable in the real-world (Bishop, 2008).

In Chapter 7, the loading phase was found to not only independently contribute to start performance, but the success of this phase appears to be unrelated to physical capacity. Thus, the loading phase is an important aspect of performance and the determinants of a successful load were suggested to be more dependent on technique-based factors than physical factors. An alternative way to enhance skeleton start performance could therefore be through separate loading technique training. Currently, the techniques underlying effective loading phases have not been investigated and were beyond the scope of this thesis because it was only possible to instrument to sled. However, it is probable that the interaction between the sled and the athlete is fundamental to the success of the load and the overall start phase. Future research utilising motion analysis of both the sled and athlete is required and would provide valuable insight into these potential mechanisms.

8.7. Thesis conclusion

This series of investigations has provided unique longitudinal data, collected in a truly elite athletic training environment. A novel statistical approach was used to overcome several challenges associated with conducting scientific studies in this setting. This revealed three independent physical predictors of start performance, which were subsequently shown to provide a stable indication of a skeleton athlete's start ability. The controversial role of testosterone in the training process was explored, and this hormone appeared to influence the expression of push performance and lean mass accrual across a season. However, whether the insight gained surpasses the investment of time and finance remains debatable and the retrospective nature of this analysis was deemed to limit its current practical application. On the other hand, DXA scanning was uncovered as a valuable tool in which to inform athlete monitoring programmes, as meaningful body composition changes were detected in a typical training setting. A continuous sled velocity measure allowed the determinants of start performance to be examined in greater detail than ever before. Several novel start performance descriptors were formulated from the resultant sled velocity profile and their contributions to start performance were demonstrated. The ability to accelerate the sled for longer and attain higher sled velocities was strongly dependent on physical capacity. However, the emergence of a trade-off between attaining high pre-load velocities and effectively loading the sled warrants consideration, and maximising pre-load velocity may not be a

favourable strategy in certain cases. Indeed, individualised analyses revealed some scope to improve start performance by modifying loading distance, particularly for less experienced skeleton athletes.

This programme of work provides much needed scientific evidence, which can aid the preparation of skeleton athletes by informing skeleton start training and improving athlete monitoring programmes. This thesis has also demonstrated potential to manipulate aspects of the start phase to ultimately enhance skeleton start performance.

REFERENCES

- Aagaard, P. (2003). Training-induced changes in neural function. *Exercise and Sport Sciences Reviews*, 31, 61-67.
- Aagaard, P. (2004). Making muscles "stronger": Exercise, nutrition, drugs. *Journal of Musculoskeletal and Neuronal Interactions*, 4, 165-174.
- Aagaard, P., & Andersen, J. L. (1998). Correlation between contractile strength and myosin heavy chain isoform composition in human skeletal muscle. *Medicine and Science in Sports and Exercise*, 30, 1217-1222.
- Aagaard, P., Andersen, J. L., Dyhre-Poulsen, P., Leffers, A-M., Wagner, A., Magnusson, S. P., Halkjaer-Kristensen, J., & Simonsen, E. B. (2001). A mechanism for increased contractile strength of human pennate muscle in response to strength training: Changes in muscle architecture. *Journal of Physiology*, 534, 613-623.
- Aagaard, P., Simonsen, E. B., Andersen, J. L., Magnusson, P., & Dyhre-Poulsen, P. (2002a). Increased rate of force development and neural drive of human skeletal muscle following resistance training. *Journal of Applied Physiology*, 93, 1318-1326.
- Aagaard, P., Simonsen, E. B., Andersen, J. L., Magnusson, P., & Dyhre-Poulsen, P. (2002b). Neural adaptation to resistance training: Changes in evoked V-wave and H-reflex responses. *Journal of Applied Physiology*, 92, 2309-2318.
- Abernethy, P., Wilson, G., & Logan, P. (1995). Strength and power assessment: Issues, controversies and challenges. *Sports Medicine*, 19, 401-417.
- Adams, G. R., Hather, B. M., Baldwin, K. M., & Dudley, G. A. (1993). Skeletal muscle myosin heavy chain composition and resistance training. *Journal of Applied Physiology*, 74, 911-915.
- Ahtiainen, J. P., Pakarinen, A., Alén, M., Kraemer, W. J., & Häkkinen, K. (2003). Muscle hypertrophy, hormonal adaptations and strength development during strength training in strength-trained and untrained men. *European Journal of Applied Physiology*, 89, 555-563.

- Ahtiainen, J. P., Pakarinen, A., Kraemer, W. J., & Häkkinen, K. (2004). Acute hormonal responses to heavy resistance exercise in strength athletes versus nonathletes. *Canadian Journal of Applied Physiology*, 29, 527-543.
- Alexander, M. J. L. (1989). The relationship between muscle strength and sprint kinematics in elite sprinters. *Canadian Journal of Sport Sciences*, 14, 148-157.
- Alligier, M., Meugnier, E., Debard, C., Lambert-Porcheron, S., Chanseau, E., Sothier, M., Loizon, E., Hssain, A. A., Brozek, J., Scoazec, J-Y., Morio, B., Vidal, H., & Laville, M. (2012). Subcutaneous adipose tissue remodeling during the initial phase of weight gain induced by overfeeding in humans. *Journal of Clinical Endocrinology and Metabolism*, 97, E183-E192.
- Amelink, G. J., & Bar, P. R. (1986). Exercise-induced protein leakage in the rat: Effects of hormonal manipulation. *Journal of the Neurological Sciences*, 76, 61-68.
- Amonette, W. E., English, K. L., & Ottenbacher, K. J. (2010). Nullius in verba: A call for the incorporation of evidence-based practice into the discipline of exercise science. *Sports Medicine*, 40, 449-457.
- Andersen, J. L., & Aagaard, P. (2000). Myosin heavy chain IIX overshoot in human skeletal muscle. *Muscle and Nerve*, 23, 1095-1104.
- Anderson, M. A., Gieck, J. H., Perrin, D., Weltman, A., Rutt, R., & Denegar, C. (1991). The relationships among isometric, isotonic, and isokinetic concentric and eccentric quadriceps and hamstring force and three components of athletic performance. *Journal of Orthopaedic and Sports Physical Therapy*, 14, 114-120.
- Aragón-Vargas, L. F. (2000). Evaluation of four vertical jump tests: Methodology, reliability, validity, and accuracy. *Measurement in Physical Education and Exercise Science*, 4, 215-228.
- Åstrand, P-O., & Rodahl, K. (1977). *Textbook of work physiology*. (2nd ed.). New York: McGraw-Hill.
- Atwater, A. E. (1982). Kinematic analyses of sprinting. *Track and Field Quarterly Review*, 82(2), 12-16.

- Aubets, J., & Segura, J. (1995). Salivary cortisol as a marker of competition related stress. *Science and Sports*, 10, 149-154.
- Baker, D. (1996). Improving vertical jump performance through general, special, and specific strength training: A brief review. *Journal of Strength and Conditioning Research*, 10, 131-136.
- Baker, D., & Nance, S. (1999). The relation between running speed and measures of strength and power in professional rugby league players. *Journal of Strength and Conditioning Research*, 13, 230-235.
- Bates, B. T., James, C. R., & Dufek, J. S. (2004). Single-subject analysis. In N. Stergiou (Ed.), *Innovative analyses of human movement* (pp. 3-28). Champaign, IL: Human Kinetics.
- Batterham, A. M., & Hopkins, W. G. (2006). Making meaningful inferences about magnitudes. *International Journal of Sports Physiology and Performance*, 1, 50-57.
- Bauer, E. R. S., Daxenberger, A., Petri, T., Sauerwein, H., & Meyer, H. H. D. (2000). Characterisation of the affinity of different anabolics and synthetic hormones to the human androgen receptor, human sex hormone binding globulin and to the bovine progestin receptor. *APMIS*, 108, 838-846.
- Baumann, W. (1976). Kinematic and dynamic characteristics of the sprint start. In P. V. Komi (Ed.), *Biomechanics V-B* (pp. 194-199). Baltimore, MD: University Park Press.
- Beaven, C. M., Cook, C. J., & Gill, N. D. (2008a). Significant strength gains observed in rugby players after specific resistance exercise protocols based on individual salivary testosterone responses. *Journal of Strength and Conditioning Research*, 22, 419-425.
- Beaven, C. M., Gill, N. D., & Cook, C. J. (2008b). Salivary testosterone and cortisol responses in professional rugby players after four resistance exercise protocols. *Journal of Strength and Conditioning Research*, 22, 426-432.
- Bellamy, L. M., Joannis, S., Grubb, A., Mitchell, C. J., McKay, B. R., Phillips, S. M., Baker, S., & Parise, G. (2014). The acute satellite cell response and skeletal muscle hypertrophy following resistance training. *PLoS ONE*, 9, 1-10.

- Bezodis, N. E. (2009). *Biomechanical Investigations of Sprint Start Technique and Performance* (Unpublished Doctoral thesis). University of Bath, UK.
- Bezodis, N. E., Salo, A. I. T., & Trewartha, G. (2010). Choice of sprint start performance measure affects the performance-based ranking within a group of sprinters: Which is the most appropriate measure? *Sports Biomechanics*, 9, 258-269.
- Bezodis, N. E., Salo, A. I. T., & Trewartha, G. (2015). Relationships between lower-limb kinematics and block phase performance in a cross section of sprinters. *European Journal of Sport Science*, 15, 118-124.
- Bezodis, N. E., Trewartha, G., & Salo, A. I. T. (2008). Understanding elite sprint start performance through an analysis of joint kinematics. In Y-H. Kwon, J. Shim, J. K. Shim, & I-S. Shin (Eds.), *Proceedings of XXVI International Conference on Biomechanics in Sports* (pp. 498-501). Seoul, Korea: Seoul National University Press.
- Bhasin, S., Woodhouse, L., Casaburi, R., Singh, A. B., Bhasin, D., Berman, N., Chen, X., Yarasheski, K. E., Magliano, L., Dzekov, C., Dzekov, J., Bross, R., Phillips, J., Sinha-Hikim, I., Shen, R. Q., & Storer, T. W. (2001a). Testosterone dose-response relationships in healthy young men. *American Journal of Physiology - Endocrinology and Metabolism*, 281, E1172-E1181.
- Bhasin, S., Woodhouse, L., & Storer, T. W. (2001b). Proof of the effect of testosterone on skeletal muscle. *Journal of Endocrinology*, 170, 27-38.
- Bishop, D. (2008). An applied research model for the sport sciences. *Sports Medicine*, 38, 253-263.
- Blazevich, A. J., & Jenkins, D. G. (2002). Effect of the movement speed of resistance training exercises on sprint and strength performance in concurrently training elite junior sprinters. *Journal of Sports Sciences*, 20, 981-990.
- Bloom, S. R., Johnson, R. H., Park, D. M., Rennie, M. J., & Sulaiman, W. R. (1976). Differences in the metabolic and hormonal response to exercise between racing cyclists and untrained individuals. *Journal of Physiology*, 258, 1-18.

- Bobbert, M. F. (2012). Why is the force-velocity relationship in leg press tasks quasi-linear rather than hyperbolic? *Journal of Applied Physiology*, 112, 1975-1983.
- Book, A. S., Starzyk, K. B., & Quinsey, V. L. (2001). The relationship between testosterone and aggression: A meta-analysis. *Aggression and Violent Behavior*, 6, 579-599.
- Borresen, J., & Lambert, M. I. (2009). The quantification of training load, the training response and the effect on performance. *Sports Medicine*, 39, 779-795.
- Bosco, C., & Komi, P. V. (1980). Influence of aging on the mechanical behavior of leg extensor muscles. *European Journal of Applied Physiology*, 45, 209-219.
- Bosco, C., Tihanyi, J., Rivalta, L., Parlato, G., Tranquilli, C., Pulvirenti, G., Foti, C., Viru, M., & Viru, A. (1996a). Hormonal responses in strenuous jumping effort. *Japanese Journal of Physiology*, 46, 93-98.
- Bosco, C., Tihanyi, J., & Viru, A. (1996b). Relationships between field fitness test and basal serum testosterone and cortisol levels in soccer players. *Clinical Physiology*, 16, 317-322.
- Bottinelli, R., Pellegrino, M. A., Canepari, M., Rossi, R., & Reggiani, C. (1999). Specific contributions of various muscle fibre types to human muscle performance: An in vitro study. *Journal of Electromyography and Kinesiology*, 9, 87-95.
- Breed, R. V. P., & McElroy, G. K. (2000). A biomechanical comparison of the grab, swing and track starts in swimming. *Journal of Human Movement Studies*, 39, 277-293.
- Bret, C., Rahmani, A., Dufour, A. B., Messonnier, L., & Lacour, J. R. (2002). Leg strength and stiffness as ability factors in 100m sprint running. *Journal of Sports Medicine and Physical Fitness*, 42, 274-281.
- Brommage, R. (2003). Validation and calibration of DEXA body composition in mice. *American Journal of Physiology - Endocrinology and Metabolism*, 285, E454-E459.
- Brown, J. A. C. (1954). *The Social Psychology of Industry*. Middlesex, England: Penguin.

- Bruce, S. A., Phillips, S. K., & Woledge, R. C. (1997). Interpreting the relation between force and cross-sectional area in human muscle. *Medicine and Science in Sports and Exercise*, 29, 677-683.
- Brüggemann, G. P., Morlock, M., & Zatsiorsky, V. M. (1997). Analysis of the bobsled and men's luge events at the XVII Olympic winter games in Lillehammer. *Journal of Applied Biomechanics*, 13, 98-108.
- Bullock, N., Gulbin, J. P., Martin, D. T., Ross, A., Holland, T., & Marino, F. (2009a). Talent identification and deliberate programming in skeleton: Ice novice to Winter Olympian in 14 months. *Journal of Sports Sciences*, 27, 397-404.
- Bullock, N., Hopkins, W. G., Martin, D. T., & Marino, F. E. (2009b). Characteristics of performance in skeleton World Cup races. *Journal of Sports Sciences*, 27, 367-372.
- Bullock, N., Martin, D. T., Ross, A., Rosemond, D., Holland, T., & Marino, F. E. (2008). Characteristics of the start in women's World Cup skeleton. *Sports Biomechanics*, 7, 351-360.
- Burke, E. J. (1976). Validity of selected laboratory and field tests of physical working capacity. *Research Quarterly*, 47, 95-104.
- Burke, L. M., Gollan, R. A., & Read, R. S. (1986). Seasonal changes in body composition in Australian Rules footballers. *British Journal of Sports Medicine*, 20, 69-71.
- Byrne, C., & Eston, R. (2002). The effect of exercise-induced muscle damage on isometric and dynamic knee extensor strength and vertical jump performance. *Journal of Sports Sciences*, 20, 417-425.
- Byrne, C., Twist, C., & Eston, R. (2004). Neuromuscular function after exercise-induced muscle damage. *Sports Medicine*, 34, 49-69.
- Byrnes, W. C., Clarkson, P. M., White, J. S., Hsieh, S. S., Frykman, P. N., & Maughan, R. J. (1985). Delayed onset muscle soreness following repeated bouts of downhill running. *Journal of Applied Physiology*, 59, 710-715.

- Callister, R., Callister, R. J., Staron, R. S., Fleck, S. J., Tesch, P., & Dudley, G. A. (1991). Physiological characteristics of elite judo athletes. *International Journal of Sports Medicine*, 12, 196-203.
- Cardinale, M., & Stone, M. H. (2006). Is testosterone influencing explosive performance? *Journal of Strength and Conditioning Research*, 20, 103-107.
- Chen, Y. Z., Hua, S. Y., Wang, C. A., Wu, L. G., Gu, Q., & Xing, B. R. (1991). An electrophysiological study on the membrane receptor-mediated action of glucocorticoids in mammalian neurons. *Neuroendocrinology*, 53, 25-30.
- Christ, C. B., Slaughter, M. H., Stillman, R. J., Cameron, J., & Boileau, R. A. (1994). Reliability of select parameters of isometric muscle function associated with testing 3 days x 3 trials in women. *Journal of Strength and Conditioning Research*, 8, 65-71.
- Clarkson, P. M., & Hubal, M. J. (2002). Exercise-induced muscle damage in humans. *American Journal of Physical Medicine and Rehabilitation*, 81, S52-S69.
- Clarkson, P. M., Nosaka, K., & Braun, B. (1992). Muscle function after exercise-induced muscle damage and rapid adaptation. *Medicine and Science in Sports and Exercise*, 24, 512-520.
- Clarkson, P. M., & Sayers, S. P. (1999). *Gender differences in exercise-induced muscle damage*. Boca Raton, FL: CRC Press.
- Clarkson, P. M., & Tremblay, I. (1988). Exercise-induced muscle damage, repair, and adaptation in humans. *Journal of Applied Physiology*, 65, 1-6.
- Cohen, J. (1988). *Statistical power analysis for the behavioural sciences*. (2nd ed.). Hillsdale, NJ: Lawrence Erlbaum.
- Cook, C. J., & Beaven, C. M. (2013). Salivary testosterone is related to self-selected training load in elite female athletes. *Physiology and Behavior*, 116, 8-12.
- Cook, C. J., & Crewther, B. T. (2012). Changes in salivary testosterone concentrations and subsequent voluntary squat performance following the presentation of short video clips. *Hormones and Behavior*, 61, 17-22.

- Cook, C. J., Crewther, B. T., & Kilduff, L. P. (2013). Are free testosterone and cortisol concentrations associated with training motivation in elite male athletes? *Psychology of Sport and Exercise, 14*, 882-885.
- van Coppenolle, H., Delecluse, C., Goris, M., Bohets, W., & Vanden Eynde, E. (1989). Technology and development of speed: Evaluation of the start, sprint and body composition of Pavoni, Cooman and Desruelles. *Athletics Coach, 23*(1), 82-90.
- Cormie, P., McCaulley, G. O., & McBride, J. M. (2007). Power versus strength-power jump squat training: Influence on the load-power relationship. *Medicine and Science in Sports and Exercise, 39*, 996-1003.
- Costill, D. L. (1970). Metabolic responses during distance running. *Journal of Applied Physiology, 28*, 251-255.
- Coyle, E. F., Coggan, A. R., Hopper, M. K., & Walters, T. J. (1988). Determinants of endurance in well-trained cyclists. *Journal of Applied Physiology, 64*, 2622-2630.
- Craib, M. W., Mitchell, V. A., Fields, K. B., Cooper, T. R., Hopewell, R., & Morgan, D. W. (1996). The association between flexibility and running economy in sub-elite male distance runners. *Medicine and Science in Sports and Exercise, 28*, 737-743.
- Crewther, B., Cronin, J., Keogh, J., & Cook, C. (2008). The salivary testosterone and cortisol response to three loading schemes. *Journal of Strength and Conditioning Research, 22*, 250-255.
- Crewther, B., Keogh, J., Cronin, J., & Cook, C. (2006). Possible stimuli for strength and power adaptation: Acute hormonal responses. *Sports Medicine, 36*, 215-238.
- Crewther, B. T., Cook, C., Cardinale, M., Weatherby, R. P., & Lowe, T. (2011). Two emerging concepts for elite athletes: The short-term effects of testosterone and cortisol on the neuromuscular system and the dose-response training role of these endogenous hormones. *Sports Medicine, 41*, 103-123.
- Crewther, B. T., Cook, C. J., Gaviglio, C. M., Kilduff, L. P., & Drawer, S. (2012a). Baseline strength can influence the ability of salivary free testosterone to predict squat

and sprinting performance. *Journal of Strength and Conditioning Research*, 26, 261-268.

Crewther, B. T., Heke, T., & Keogh, J. W. L. (2013). The effects of a resistance-training program on strength, body composition and baseline hormones in male athletes training concurrently for rugby union 7's. *Journal of Sports Medicine and Physical Fitness*, 53, 34-41.

Crewther, B. T., Kilduff, L. P., Cook, C. J., Cunningham, D. J., Bunce, P., Bracken, R. M., & Gaviglio, C. M. (2012b). Relationships between salivary free testosterone and the expression of force and power in elite athletes. *Journal of Sports Medicine and Physical Fitness*, 52, 221-227.

Crewther, B. T., Lowe, T., Weatherby, R. P., Gill, N., & Keogh, J. (2009). Neuromuscular performance of elite rugby union players and relationships with salivary hormones. *Journal of Strength and Conditioning Research*, 23, 2046-2053.

Cronin, J. B., & Hansen, K. T. (2005). Strength and power predictors of sports speed. *Journal of Strength and Conditioning Research*, 19, 349-357.

Cronin, J. B., McNair, P. J., & Marshall, R. N. (2002). Is velocity-specific strength training important in improving functional performance? *Journal of Sports Medicine and Physical Fitness*, 42, 267-273.

Crossland, B. W., Hartman, J. E., Kilgore, J. L., Hartman, M. J., & Kaus, J. M. (2011). Upper-body anthropometric and strength measures and their relationship to start time in elite luge athletes. *Journal of Strength and Conditioning Research*, 25, 2639-2644.

Cumming, G. (2012). *Understanding the new statistics: Effect sizes, confidence intervals, and meta-analysis*. New York, NY: Routledge.

Cumming, G., & Finch, S. (2001). A primer on the understanding, use, and calculation of confidence intervals that are based on central and noncentral distributions. *Educational and Psychological Measurement*, 61, 532-574.

- van Cutsem, M., Duchateau, J., & Hainaut, K. (1998). Changes in single motor unit behaviour contribute to the increase in contraction speed after dynamic training in humans. *Journal of Physiology*, 513, 295-305.
- Dabbs, J. M., Jr. (1990). Salivary testosterone measurements: Reliability across hours, days, and weeks. *Physiology and Behavior*, 48, 83-86.
- Dawson, B., Fitzsimons, M., Green, S., Goodman, C., Carey, M., & Cole, K. (1998). Changes in performance, muscle metabolites, enzymes and fibre types after short sprint training. *European Journal of Applied Physiology and Occupational Physiology*, 78, 163-169.
- De Bosscher, V., De Knop, P., van Bottenburg, M., Shibli, S., & Bingham, J. (2009). Explaining international sporting success: An international comparison of elite sport systems and policies in six countries. *Sport Management Review*, 12, 113-136.
- De Lorenzo, A., Andreoli, A., & Candeloro, N. (1997). Within-subject variability in body composition using dual-energy X-ray absorptiometry. *Clinical Physiology*, 17, 383-388.
- Delecluse, C. (1997). Influence of strength training on sprint running performance. *Sports Medicine*, 24, 147-156.
- Dixon, S. J., & Kerwin, D. G. (2002). Variations in achilles tendon loading with heel lift intervention in heel-toe runners. *Journal of Applied Biomechanics*, 18, 321-331.
- Douda, H. T., Toubekis, A. G., Avloniti, A. A., & Tokmakidis, S. P. (2008). Physiological and anthropometric determinants of rhythmic gymnastics performance. *International Journal of Sports Physiology and Performance*, 3, 41-54.
- Dowson, M. N., Nevill, M. E., Lakomy, H. K. A., Nevill, A. M., & Hazeldine, R. J. (1998). Modelling the relationship between isokinetic muscle strength and sprint running performance. *Journal of Sports Sciences*, 16, 257-265.
- Dunn, J. F., Nisula, B. C., & Rodbard, D. (1981). Transport of steroid hormones: Binding of 21 endogenous steroids to both testosterone-binding globulin and

corticosteroid-binding globulin in human plasma. *Journal of Clinical Endocrinology and Metabolism*, 53, 58-68.

Egan, E., Wallace, J., Reilly, T., Chantler, P., & Lawlor, J. (2006). Body composition and bone mineral density changes during a premier league season as measured by dual-energy X-ray absorptiometry. *International Journal of Body Composition Research*, 4, 61-66.

Esfarjani, F., & Laursen, P. B. (2007). Manipulating high-intensity interval training: Effects on $\dot{V}O_{2max}$, the lactate threshold and 3000 m running performance in moderately trained males. *Journal of Science and Medicine in Sport*, 10, 27-35.

Estrada, M., Espinosa, A., Müller, M., & Jaimovich, E. (2003). Testosterone stimulates intracellular calcium release and mitogen-activated protein kinases via a G protein-coupled receptor in skeletal muscle cells. *Endocrinology*, 144, 3586-3597.

Estrada, M., Liberona, J. L., Miranda, M., & Jaimovich, E. (2000). Aldosterone- and testosterone-mediated intracellular calcium response in skeletal muscle cell cultures. *American Journal of Physiology - Endocrinology and Metabolism*, 279, E132-E139.

Evertsen, F., Medbø, J. I., & Bonen, A. (2001). Effect of training intensity on muscle lactate transporters and lactate threshold of cross-country skiers. *Acta Physiologica Scandinavica*, 173, 195-205.

FIBT (2010). FIBT International Skeleton Rules. Available from <http://www.fibt.com/index.php?id=50>. [Accessed 19 October 2011].

FIBT (2015a). Official Race Results. Available from <http://www.fibt.com/races-results/results.html>. [Accessed 22 January 2015].

FIBT (2015b). Tracks. Available from <http://www.fibt.com/races-results/tracks.html>. [Accessed 9 April 2015].

Field, A. P. (2000). *Discovering statistics using SPSS for Windows: Advanced techniques for the beginner*. London, UK: SAGE.

Fleck, S. J. (1999). Periodized strength training: A critical review. *Journal of Strength and Conditioning Research*, 13, 82-89.

- Folland, J. P., & Williams, A. G. (2007). The adaptations to strength training: Morphological and neurological contributions to increased strength. *Sports Medicine*, 37, 145-168.
- Fortier, S., Basset, F. A., Mbourou, G. A., Favérial, J., & Teasdale, N. (2005). Starting block performance in sprinters: A statistical method for identifying discriminative parameters of the performance and an analysis of the effect of providing feedback over a 6-week period. *Journal of Sports Science and Medicine*, 4, 134-143.
- Fry, A. C. (2004). The role of resistance exercise intensity on muscle fibre adaptations. *Sports Medicine*, 34, 663-679.
- Fuller, N. J., Laskey, M. A., & Elia, M. (1992). Assessment of the composition of major body regions by dual-energy X-ray absorptiometry (DEXA), with special reference to limb muscle mass. *Clinical Physiology*, 12, 253-266.
- Gabbett, T. J. (2005). Changes on physiological and anthropometric characteristics of rugby league players during a competitive season. *Journal of Strength and Conditioning Research*, 19, 400-408.
- Gabriel, D. A., Kamen, G., & Frost, G. (2006). Neural adaptations to resistive exercise: Mechanisms and recommendations for training practices. *Sports Medicine*, 36, 133-149.
- Godoy, A., Kawinski, E., Li, Y., Oka, D., Alexiev, B., Azzouni, F., Titus, M. A., & Mohler, J. L. (2011). 5 α -reductase type 3 expression in human benign and malignant tissues: A comparative analysis during prostate cancer progression. *Prostate*, 71, 1033-1046.
- Goodwin, P. C., Koorts, K., Mack, R., Mai, S., Morrissey, M. C., & Hooper, D. M. (1999). Reliability of leg muscle electromyography in vertical jumping. *European Journal of Applied Physiology*, 79, 374-378.
- Guissard, N., & Duchateau, J. (1990). Electromyography of the sprint start. *Journal of Human Movement Studies*, 18, 97-106.

- Guissard, N., Duchateau, J., & Hainaut, K. (1992). EMG and mechanical changes during sprint starts at difference front block obliquities. *Medicine and Science in Sports and Exercise*, 24, 1257-1263.
- Gutin, B., Litaker, M., Islam, S., Manos, T., Smith, C., & Treiber, F. (1996). Body-composition measurement in 9-11-y-old children by dual-energy X-ray absorptiometry, skinfold-thickness measurements, and bioimpedance analysis. *American Journal of Clinical Nutrition*, 63, 287-292.
- Haarbo, J., Gotfredsen, A., Hassager, C., & Christiansen, C. (1991). Validation of body composition by dual energy X-ray absorptiometry (DEXA). *Clinical Physiology*, 11, 331-341.
- Hair, J. F., Black, W. C., Babin, B. J., & Anderson, R. E. (2009). *Multivariate data analysis: A global perspective*. (7th ed.). Upper Saddle River, NJ: Pearson.
- Häkkinen, K. (1985). Factors influencing trainability of muscular strength during short term and prolonged training. *National Strength and Conditioning Association Journal*, 7, 32-37.
- Häkkinen, K. (1989). Neuromuscular and hormonal adaptation during strength and power training: A review. *Journal of Sports Medicine and Physical Fitness*, 29, 9-26.
- Häkkinen, K., Alén, M., & Komi, P. V. (1985a). Changes in isometric force- and relaxation-time, electromyographic and muscle fibre characteristics of human skeletal muscle during strength training and detraining. *Acta Physiologica Scandinavica*, 125, 573-585.
- Häkkinen, K., Komi, P. V., & Alén, M. (1985b). Effect of explosive type strength training on isometric force- and relaxation-time electromyographic and muscle-fibre characteristics of leg extensor muscles. *Acta Physiologica Scandinavica*, 125, 587-600.
- Häkkinen, K., & Pakarinen, A. (1991). Serum hormones in male strength athletes during intensive short term strength training. *European Journal of Applied Physiology and Occupational Physiology*, 63, 194-199.

- Häkkinen, K., & Pakarinen, A. (1993). Acute hormonal responses to two different fatiguing heavy-resistance protocols in male athletes. *Journal of Applied Physiology*, 74, 882-887.
- Häkkinen, K., & Pakarinen, A. (1995). Acute hormonal responses to heavy resistance exercise in men and women at different ages. *International Journal of Sports Medicine*, 16, 507-513.
- Häkkinen, K., Pakarinen, A., Alén, M., Kauhanen, H., & Komi, P. V. (1988). Neuromuscular and hormonal adaptations in athletes to strength training in two years. *Journal of Applied Physiology*, 65, 2406-2412.
- Häkkinen, K., Pakarinen, A., Alén, M., & Komi, P. V. (1985c). Serum hormones during prolonged training of neuromuscular performance. *European Journal of Applied Physiology and Occupational Physiology*, 53, 287-293.
- Häkkinen, K., Pakarinen, A., Kyröläinen, H., Cheng, S., Kim, D. H., & Komi, P. V. (1990). Neuromuscular adaptations and serum hormones in females during prolonged power training. *International Journal of Sports Medicine*, 11, 91-98.
- Hamdi, M. M., & Mutungi, G. (2010). Dihydrotestosterone activates the MAPK pathway and modulates maximum isometric force through the EGF receptor in isolated intact mouse skeletal muscle fibres. *Journal of Physiology*, 588, 511-525.
- Hamdi, M. M., & Mutungi, G. (2011). Dihydrotestosterone stimulates amino acid uptake and the expression of LAT2 in mouse skeletal muscle fibres through an ERK1/2-dependent mechanism. *Journal of Physiology*, 589, 3623-3640.
- Harland, M. J., & Steele, J. R. (1997). Biomechanics of the sprint start. *Sports Medicine*, 23, 11-20.
- Harley, J. A., Hind, K., & O'Hara, J. P. (2011). Three-compartment body composition changes in elite rugby league players during a super league season, measured by dual-energy X-ray absorptiometry. *Journal of Strength and Conditioning Research*, 25, 1024-1029.

- Harris, G. R., Stone, M. H., O'Bryant, H. S., Proulx, C. M., & Johnson, R. L. (2000). Short-term performance effects of high power, high force, or combined weight-training methods. *Journal of Strength and Conditioning Research*, 14, 14-20.
- Hastie, T., Tibshirani, R., & Friedman, J. H. (2009). *The elements of statistical learning: Data mining, inference, and prediction*. (2nd ed.). New York, NY: Springer.
- Hayes, L. D., Bickerstaff, G. F., & Baker, J. S. (2010). Interactions of cortisol, testosterone, and resistance training: Influence of circadian rhythms. *Chronobiology International*, 27, 675-705.
- Hedayatpour, N., Falla, D., Arendt-Nielsen, L., & Farina, D. (2008). Sensory and electromyographic mapping during delayed-onset muscle soreness. *Medicine and Science in Sports and Exercise*, 40, 326-334.
- Hennessy, L., & Kilty, J. (2001). Relationship of the stretch-shortening cycle to sprint performance in trained female athletes. *Journal of Strength and Conditioning Research*, 15, 326-331.
- Henry, F. M. (1952). Force-time characteristics of the sprint start. *Research Quarterly*, 23, 301-318.
- Holm, L., Haslund, M. L., Robach, P., van Hall, G., Calbet, J. A. L., Saltin, B., & Lundby, C. (2010). Skeletal muscle myofibrillar and sarcoplasmic protein synthesis rates are affected differently by altitude-induced hypoxia in native lowlanders. *PloS One*, 5, e15606.
- Hopkins, W. G. (2000a). Measures of reliability in sports medicine and science. *Sports Medicine*, 30, 1-15.
- Hopkins, W. G. (2000b). Precision of the measurement. Available from <http://www.newstats.org/precision.html>. [Accessed 25 April 2014].
- Hopkins, W. G. (2006a). Estimating sample size for magnitude-based inferences. *Sportscience*, 63-70.

Hopkins, W. G. (2006b). A spreadsheet for combining outcomes from several subject groups. Available from <http://www.sportsci.org/2006/wghcom.htm>. [Accessed 7 March 2014].

Hopkins, W. G. (2006c). A spreadsheet for estimating sample-size for magnitude-based inferences. Available from <http://www.sportsci.org/resource/stats/xSampleSize.xlsx>. [Accessed 18 May 2014].

Hopkins, W. G. (2006d). Spreadsheets for analysis of controlled trials with adjustment for a predictor. Available from <http://www.sportsci.org/2006/wghcontrial.htm>. [Accessed 22 January 2014].

Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine and Science in Sports and Exercise*, 41, 3-12.

Horber, F. F., Thomi, F., Casez, J. P., Fonteille, J., & Jaeger, P. (1992). Impact of hydration status on body composition as measured by dual energy X-ray absorptiometry in normal volunteers and patients on haemodialysis. *British Journal of Radiology*, 65, 895-900.

Hori, N., Newton, R. U., Andrews, W. A., Kawamori, N., McGuigan, M. R., & Nosaka, K. (2008). Does performance of hang power clean differentiate performance of jumping, sprinting, and changing of direction? *Journal of Strength and Conditioning Research*, 22, 412-418.

Hubley-Kozey, C. L. (1991). Testing flexibility. In J. D. MacDougall, H. A. Wenger, & H. J. Green (Eds.), *Physiological testing of the high-performance athlete* (2nd ed.) (pp. 309-359). Champaign, IL: Human Kinetics.

Hunter, J. P., Marshall, R. N., & McNair, P. (2005). Relationships between ground reaction force impulse and kinematics of sprint-running acceleration. *Journal of Applied Biomechanics*, 21, 31-43.

Hunter, J. P., Marshall, R. N., & McNair, P. J. (2004). Interaction of step length and step rate during sprint running. *Medicine and Science in Sports and Exercise*, 36, 261-271.

- van Ingen Schenau, G. J., Jacobs, R., & de Koning, J. J. (1991). Can cycle power predict sprint running performance? *European Journal of Applied Physiology and Occupational Physiology*, 63, 255-260.
- van Ingen Schenau, G. J., de Koning, J. J., & de Groot, G. (1994). Optimisation of sprinting performance in running, cycling and speed skating. *Sports Medicine*, 17, 259-275.
- Jackson, A. S., & Pollock, M. L. (1978). Generalized equations for predicting body density of men. *British Journal of Nutrition*, 40, 497-504.
- Jacobs, R., & van Ingen Schenau, G. J. (1992). Intermuscular coordination in a sprint push-off. *Journal of Biomechanics*, 25, 953-965.
- Jones, A. M. (1998). A five year physiological case study of an Olympic runner. *British Journal of Sports Medicine*, 32, 39-43.
- Jones, D. A., Rutherford, O. M., & Parker, D. F. (1989). Physiological changes in skeletal muscle as a result of strength training. *Quarterly Journal of Experimental Physiology*, 74, 233-256.
- Kaneko, M., Fuchimoto, T., Toji, H., & Suei, K. (1983). Training effect of different loads on the force-velocity relationship and mechanical power output in human muscle. *Scandinavian Journal of Sports Science*, 5, 50-55.
- Kearney, J. T. (1999). Sport performance enhancement: Design and analysis of research. *Medicine and Science in Sports and Exercise*, 31, 755-756.
- Kelley, G. (1996). Mechanical overload and skeletal muscle fiber hyperplasia: a meta-analysis. *Journal Applied Physiology*, 81, 1584-1588.
- Kendall, B., & Eston, R. (2002). Exercise-induced muscle damage and the potential protective role of estrogen. *Sports Medicine*, 32, 103-123.
- Kivi, D. M. R., Maraj, B. K. V., & Gervais, P. (2002). A kinematic analysis of high-speed treadmill sprinting over a range of velocities. *Medicine and Science in Sports and Exercise*, 34, 662-666.

- Kleinbaum, D. G., Kupper, L. L., & Muller, K. E. (1988). *Applied regression analysis and other multivariable methods*. (2nd ed.). Boston, MA: Kent Publishing Company.
- Klipstein-Grobusch, K., Georg, T., & Boeing, H. (1997). Interviewer variability in anthropometric measurements and estimates of body composition. *International Journal of Epidemiology*, 26, S174-S180.
- Knudson, D. (2005). Evidence-based practice in kinesiology: The theory to practice gap revisited. *The Physical Educator*, 62, 212-221.
- de Koning, J. J., de Groot, G., & van Ingen Schenau, G. J. (1992). A power equation for the sprint in speed skating. *Journal of Biomechanics*, 25, 573-580.
- Kraemer, W. J., Deschenes, M. R., & Fleck, S. J. (1988). Physiological adaptations to resistance exercise: Implications for athletic conditioning. *Sports Medicine*, 6, 246-256.
- Kraemer, W. J., & Ratamess, N. A. (2004). Fundamentals of resistance training: Progression and exercise prescription. *Medicine and Science in Sports and Exercise*, 36, 674-688.
- Kraemer, W. J., & Ratamess, N. A. (2005). Hormonal responses and adaptations to resistance exercise and training. *Sports Medicine*, 35, 339-361.
- Krieger, J. W., Sitren, H. S., Daniels, M. J., & Langkamp-Henken, B. (2006). Effects of variation in protein and carbohydrate intake on body mass and composition during energy restriction: A meta-regression. *American Journal of Clinical Nutrition*, 83, 260-274.
- Kukolj, M., Ropret, R., Ugarkovic, D., & Jaric, S. (1999). Anthropometric, strength, and power predictors of sprinting performance. *Journal of Sports Medicine and Physical Fitness*, 39, 120-122.
- Le Meur, Y., Hausswirth, C., & Mujika, I. (2012). Tapering for competition: A review. *Science and Sports*, 27, 77-87.
- Le Rossignol, P., Gabbett, T. J., Comerford, D., & Stanton, W. R. (2014). Repeated-sprint ability and team selection in Australian football league players. *International Journal of Sports Physiology and Performance*, 9, 161-165.

- Legaz, A., & Eston, R. (2005). Changes in performance, skinfold thicknesses, and fat patterning after three years of intense athletic conditioning in high level runners. *British Journal of Sports Medicine*, 39, 851-856.
- Liebermann, D. G., & Katz, L. (2003). On the assessment of lower-limb muscular power capability. *Isokinetics and Exercise Science*, 11, 87-94.
- Linnamo, V., Pakarinen, A., Komi, P. V., Kraemer, W. J., & Häkkinen, K. (2005). Acute hormonal responses to submaximal and maximal heavy resistance and explosive exercises in men and women. *Journal of Strength and Conditioning Research*, 19, 566-571.
- Luhtanen, P., & Komi, P. V. (1978). Mechanical factors influencing running speed. In E. Asmussen, & K. Jørgensen (Eds.), *Biomechanics VI-B* (pp. 23-29). Baltimore: University Park Press.
- Luu-The, V., & Labrie, F. (2010). The intracrine sex steroid biosynthesis pathways. *Progress in Brain Research*, 181, 177-192.
- MacDougall, J., Wenger, H. A., & Green, H. J. (1991). *Physiological testing of the high-performance athlete*. (2nd ed.). Champaign, Ill: Human Kinetics.
- Mann, R., & Sprague, P. (1980). A kinetic analysis of the ground leg during sprint running. *Research Quarterly for Exercise and Sport*, 51, 334-348.
- Mann, R., & Sprague, P. (1983). Kinetics of sprinting. In J. Terauds (Ed.), *Proceedings of I International Symposium on Biomechanics in Sports* (pp. 305-316). San Diego, CA: University Press.
- Manni, A., Pardridge, W. M., Cefalu, W., Nisula, B. C., Bardin, C. W., Santner, S. J., & Santen, R. J. (1985). Bioavailability of albumin-bound testosterone. *Journal of Clinical Endocrinology and Metabolism*, 61, 705-710.
- Manou, V., Saraslanidis, P., Zafeiridis, A., & Kellis, S. (2003). Sitting vs. prone position isokinetic strength in elite male and female sprinters: Relationship with sprinting performance. *Journal of Human Movement Studies*, 45, 273-290.

- Markovic, G. (2007). Poor relationship between strength and power qualities and agility performance. *Journal of Sports Medicine and Physical Fitness*, 47, 276-83.
- Martindale, R., & Nash, C. (2013). Sport science relevance and application: Perceptions of UK coaches. *Journal of Sports Sciences*, 31, 807-819.
- Maughan, R. J., Watson, J. S., & Weir, J. (1983). Strength and cross-sectional area of human skeletal muscle. *Journal of Physiology*, 338, 37-49.
- Maulder, P. S., Bradshaw, E. J., & Keogh, J. (2006). Jump kinetic determinants of sprint acceleration performance from starting blocks in male sprinters. *Journal of Sports Science and Medicine*, 5, 359-366.
- Mazess, R. B., Barden, H. S., Bisek, J. P., & Hanson, J. (1990). Dual-energy X-ray absorptiometry for total-body and regional bone-mineral and soft-tissue composition. *American Journal of Clinical Nutrition*, 51, 1106-1112.
- McBride, J. M., Triplett-McBride, T., Davie, A., & Newton, R. U. (1999). A comparison of strength and power characteristics between power lifters, Olympic lifters, and sprinters. *Journal of Strength and Conditioning Research*, 13, 58-66.
- McBride, J. M., Triplett-McBride, T., Davie, A., & Newton, R. U. (2002). The effect of heavy- vs. light-load jump squats on the development of strength, power, and speed. *Journal of Strength and Conditioning Research*, 16, 75-82.
- McCall, C., & Singer, T. (2012). The animal and human neuroendocrinology of social cognition, motivation and behavior. *Nature Neuroscience*, 15, 681-688.
- McCall, G. E., Byrnes, W. C., Fleck, S. J., Dickinson, A., & Kraemer, W. J. (1999). Acute and chronic hormonal responses to resistance training designed to promote muscle hypertrophy. *Canadian Journal of Applied Physiology*, 24, 96-107.
- McCaulley, G. O., McBride, J. M., Cormie, P., Hudson, M. B., Nuzzo, J. L., Quindry, J. C., & Triplett, N. T. (2009). Acute hormonal and neuromuscular responses to hypertrophy, strength and power type resistance exercise. *European Journal of Applied Physiology*, 105, 695-704.

- McGrath, J. A., & Goldspink, D. F. (1982). Glucocorticoid action on protein synthesis and protein breakdown in isolated skeletal muscles. *Biochemical Journal*, 206, 641-645.
- McGuigan, M. R., & Cormack, S. (2011). Biochemical monitoring in strength and conditioning. In M. Cardinale, R. Newton, & K. Nosaka (Eds.), *Strength and conditioning: Biological principles and practical applications* (pp. 305-315). Chichester, UK: John Wiley & Sons.
- McGuigan, M. R., Egan, A. D., & Foster, C. (2004). Salivary cortisol responses and perceived exertion during high intensity and low intensity bouts of resistance exercise. *Journal of Sports Science and Medicine*, 3, 8-15.
- McHugh, M. P., Connolly, D. A. J., Eston, R. G., & Gleim, G. W. (1999). Exercise-induced muscle damage and potential mechanisms for the repeated bout effect. *Sports Medicine*, 27, 157-170.
- McLellan, C. P., Lovell, D. I., & Gass, G. C. (2011). The role of rate of force development on vertical jump performance. *Journal of Strength and Conditioning Research*, 25, 379-385.
- McNamee, M. J., Olivier, S., & Wainwright, P. (2007). *Research ethics in exercise, health and sports sciences*. Abingdon, UK: Routledge.
- McNeal, J. R., & Sands, W. A. (2006). Stretching for performance enhancement. *Current Sports Medicine Reports*, 5, 141-146.
- Meckel, Y., Atterbom, H., Grodjinovsky, A., Ben-Sira, D., & Rotstein, A. (1995). Physiological characteristics of female 100 metre sprinters of different performance levels. *Journal of Sports Medicine and Physical Fitness*, 35, 169-175.
- Melzack, R. (1975). The McGill pain questionnaire: Major properties and scoring methods. *Pain*, 1, 277-299.
- Mendoza, L., & Schöllhorn, W. (1993). Training of the sprint start technique with biomechanical feedback. *Journal of Sports Sciences*, 11, 25-29.

- Mermier, C. M., Janot, J. M., Parker, D. L., & Swan, J. G. (2000). Physiological and anthropometric determinants of sport climbing performance. *British Journal of Sports Medicine*, 34, 359-365.
- Mero, A. (1988). Force-time characteristics and running velocity of male sprinters during the acceleration phase of sprinting. *Research Quarterly for Exercise and Sport*, 59, 94-98.
- Mero, A., & Komi, P. V. (1990). Reaction time and electromyographic activity during a sprint start. *European Journal of Applied Physiology and Occupational Physiology*, 61, 73-80.
- Mero, A., Komi, P. V., & Gregor, R. J. (1992). Biomechanics of sprint running: A review. *Sports Medicine*, 13, 376-392.
- Mero, A., Kuitunen, S., Harland, M., Kyröläinen, & Komi, P. V. (2006). Effects of muscle-tendon length on joint moment and power during sprint starts. *Journal of Sports Sciences*, 24, 165-173.
- Mero, A., Luhtanen, P., & Komi, P. V. (1983). A biomechanical study of the sprint start. *Scandinavian Journal of Sports Science*, 5, 20-28.
- Milsom, J., Barreira, P., Burgess, D. J., Iqbal, Z., & Morton, J. P. (2014). Case study: Muscle atrophy and hypertrophy in a Premier League soccer player during rehabilitation from ACL injury. *International Journal of Sport Nutrition and Exercise Metabolism*, 24, 543-552.
- Mitchell, C. J., Churchward-Venne, T. A., Bellamy, L. M., Parise, G., Baker, S. K., & Phillips, S. M. (2013). Muscular and systemic correlates of resistance training-induced muscle hypertrophy. *PloS One*, 8, e78636.
- Moir, G., Button, C., Glaister, M., & Stone, M. H. (2004). Influence of familiarization on the reliability of vertical jump and acceleration sprinting performance in physically active men. *Journal of Strength and Conditioning Research*, 18, 276-280.
- Moir, G., Sanders, R., Button, C., & Glaister, M. (2007). The effect of periodized resistance training on accelerative sprint performance. *Sports Biomechanics*, 6, 285-300.

- Moravec, P., Ruzicka, J., Susanka, P., Dostal, E., Kodejs, M., & Nosek, M. (1988). The 1987 International Athletic Foundation/IAAF Scientific Project Report: Time analysis of the 100 metres events at the II World Championships in Athletics. *New Studies in Athletics*, 3(3), 61-96.
- Morin, J. B., Bourdin, M., Edouard, P., Peyrot, N., Samozino, P., & Lacour, J. R. (2012). Mechanical determinants of 100-m sprint running performance. *European Journal of Applied Physiology*, 112, 3921-3930.
- Moritani, T., & deVries, H. A. (1979). Neural factors versus hypertrophy in the time course of muscle strength gain. *American Journal of Physical Medicine*, 58, 115-130.
- Moss, B. M., Refsnes, P. E., Abildgaard, A., Nicolaysen, K., & Jensen, J. (1997). Effects of maximal effort strength training with different loads on dynamic strength, cross-sectional area, load-power and load-velocity relationships. *European Journal of Applied Physiology and Occupational Physiology*, 75, 193-199.
- Mougios, V. (2007). Reference intervals for serum creatine kinase in athletes. *British Journal of Sports Medicine*, 41, 674-678.
- Mujika, I., & Padilla, S. (2001). Muscular characteristics of detraining in humans. *Medicine and Science in Sports and Exercise*, 33, 1297-1303.
- Murphy, A. J., & Wilson, G. J. (1996). Poor correlations between isometric tests and dynamic performance: Relationship to muscle activation. *European Journal of Applied Physiology and Occupational Physiology*, 73, 353-357.
- Nana, A., Slater, G. J., Hopkins, W. G., & Burke, L. M. (2012). Effects of daily activities on dual-energy X-ray absorptiometry measurements of body composition in active people. *Medicine and Science in Sports and Exercise*, 44, 180-189.
- Nana, A., Slater, G. J., Hopkins, W. G., & Burke, L. M. (2013). Effects of exercise sessions on DXA measurements of body composition in active people. *Medicine and Science in Sports and Exercise*, 45, 178-185.
- Nana, A., Slater, G. J., Hopkins, W. G., Halson, S. L., Martin, D. T., West, N. P., & Burke, L. M. (2014). Importance of standardized DXA protocol for assessing physique

changes in athletes. *International Journal of Sport Nutrition and Exercise Metabolism*, 24, 10.1123/ijsnem.2013-0111 Advance online publication. doi: 10.1123/ijsnem.2013-0111.

Neary, J. P., Malbon, L., & McKenzie, D. C. (2002). Relationship between serum, saliva and urinary cortisol and its implication during recovery from training. *Journal of Science and Medicine in Sport*, 5, 108-114.

Nelson, A. G., Driscoll, N. M., Landin, D. K., Young, M. A., & Schexnayder, I. C. (2005). Acute effects of passive muscle stretching on sprint performance. *Journal of Sports Sciences*, 23, 449-454.

Nesser, T. W., Latin, R. W., Berg, K., & Prentice, E. (1996). Physiological determinants of 40-meter sprint performance in young male athletes. *Journal of Strength and Conditioning Research*, 10, 263-267.

Newton, M. J., Morgan, G. T., Sacco, P., Chapman, D. W., & Nosaka, K. (2008). Comparison of responses to strenuous eccentric exercise of the elbow flexors between resistance-trained and untrained men. *Journal of Strength and Conditioning Research*, 22, 597-607.

Newton, R. U., Cormie, P., & Cardinale, M. (2011). Principles of athlete testing. In M. Cardinale, R. U. Newton, & K. Nosaka (Eds.), *Strength and conditioning: Biological principles and practical applications* (pp. 255-270). Chichester, UK: John Wiley & Sons.

Newton, R. U., & Kraemer, W. J. (1994). Developing explosive muscular power: Implications for a mixed methods training strategy. *Strength and Conditioning Journal*, 16(5), 20-31.

Nosaka, K., & Clarkson, P. M. (1994). Effect of eccentric exercise on plasma enzyme activities previously elevated by eccentric exercise. *European Journal of Applied Physiology and Occupational Physiology*, 69, 492-497.

Nosaka, K., & Clarkson, P. M. (1995). Muscle damage following repeated bouts of high force eccentric exercise. *Medicine and Science in Sports and Exercise*, 27, 1263-1269.

- Nosaka, K., & Clarkson, P. M. (1996). Variability in serum creatine kinase response after eccentric exercise of the elbow flexors. *International Journal of Sports Medicine*, 17, 120-127.
- Nosaka, K., Newton, M., & Sacco, P. (2002). Delayed-onset muscle soreness does not reflect the magnitude of eccentric exercise-induced muscle damage. *Scandinavian Journal of Medicine and Science in Sports*, 12, 337-346.
- Nosaka, K., Sakamoto, K., Newton, M., & Sacco, P. (2001). How long does the protective effect on eccentric exercise-induced muscle damage last? *Medicine and Science in Sports and Exercise*, 33, 1490-1495.
- Oakes, M. (1986). *Statistical inference: A commentary for the social and behavioural sciences*. Chichester, UK: Wiley.
- Osbeck, J. S., Maiorca, S. N., & Rundell, K. W. (1996). Validity of field testing to bobsled start performance. *Journal of Strength and Conditioning Research*, 10, 239-245.
- Perez-Gomez, J., Rodriguez, G. V., Ara, I., Olmedillas, H., Chavarren, J., González-Henriquez, J. J., Dorado, C., & Calbet, J. A. L. (2008). Role of muscle mass on sprint performance: Gender differences? *European Journal of Applied Physiology*, 102, 685-694.
- Pette, D. (2001). Plasticity in skeletal, cardiac, and smooth muscle - Historical perspectives: Plasticity of mammalian skeletal muscle. *Journal of Applied Physiology*, 90, 1119-1124.
- Pette, D., & Staron, R. S. (1997). Mammalian skeletal muscle fibre type transitions. *International Review of Cytology*, 170, 143-223.
- Phillips, S. M. (2004). Protein requirements and supplementation in strength sports. *Nutrition*, 20, 689-695.
- Pietrobelli, A., Formica, C., Wang, Z., & Heymsfield, S. B. (1996). Dual-energy X-ray absorptiometry body composition model: Review of physical concepts. *American Journal of Physiology*, 271, E941-E951.

- Pietrobelli, A., Wang, Z., Formica, C., & Heymsfield, S. B. (1998). Dual-energy X-ray absorptiometry: Fat estimation errors due to variation in soft tissue hydration. *American Journal of Physiology*, 274, E808-E816.
- van der Ploeg, G. E., Withers, R. T., & Laforgia, J. (2003). Percent body fat via DEXA: Comparison with a four-compartment model. *Journal of Applied Physiology*, 94, 499-506.
- Pritchard, J. E., Nowson, C. A., Strauss, B. J., Carlson, J. S., Kaymakci, B., & Wark, J. D. (1993). Evaluation of dual energy X-ray absorptiometry as a method of measurement of body fat. *European Journal of Clinical Nutrition*, 47, 216-228.
- Pullinen, T., Mero, A., Huttunen, P., Pakarinen, A., & Komi, P. V. (2002). Resistance exercise-induced hormonal responses in men, women, and pubescent boys. *Medicine and Science in Sports and Exercise*, 34, 806-813.
- Putnam, C. A., & Kozey, J. W. (1989). Substantive issues in running. In C. L. Vaughan (Ed.), *Biomechanics of sport* (pp. 1-33). Boca Raton, FL: CRC Press.
- Putnam, P., Antypa, N., Crysovergi, P., & van der Does, W. A. J. (2010). Exogenous cortisol acutely influences motivated decision making in healthy young men. *Psychopharmacology*, 208, 257-263.
- Pyne, D. B., Trewin, C. B., & Hopkins, W. G. (2004). Progression and variability of competition performance of Olympic swimmers. *Journal of Sports Sciences*, 22, 613-620.
- Raastad, T., Glomsheller, T., Bjørø, T., & Hallén, J. (2001). Changes in human skeletal muscle contractility and hormone status during 2 weeks of heavy strength training. *European Journal of Applied Physiology*, 84, 54-63.
- Rhea, M. R., Alvar, B. A., Burkett, L. N., & Ball, S. D. (2003). A meta-analysis to determine the dose response for strength development. *Medicine and Science in Sports and Exercise*, 35, 456-64.
- Rimmer, E., & Sleivert, G. (2000). Effects of a plyometric intervention program on sprint performance. *Journal of Strength and Conditioning Research*, 14, 295-301.

- Robertson, D. G. E., Caldwell, G. E., Hamill, J., Kamen, G., & Whittlesey, S. N. (2004). *Research methods in biomechanics*. Champaign, IL: Human Kinetics.
- Rodenburg, J. B., Bär, P. R., & de Boer, R. W. (1993). Relations between muscle soreness and biochemical and functional outcomes of eccentric exercise. *Journal of Applied Physiology*, 74, 2976-2983.
- Rodríguez, G., Moreno, L. A., Blay, M. G., Blay, V. A., Fleta, J., Sarría, A., & Bueno, M. (2005). Body fat measurement in adolescents: Comparison of skinfold thickness equations with dual-energy X-ray absorptiometry. *European Journal of Clinical Nutrition*, 59, 1158-1166.
- Rønnestad, B. R., Nygaard, H., & Raastad, T. (2011). Physiological elevation of endogenous hormones results in superior strength training adaptation. *European Journal of Applied Physiology*, 111, 2249-2259.
- Rosnow, R. L., & Rosenthal, R. (1989). Statistical procedures and the justification of knowledge in psychological science. *American Psychologist*, 44, 1276-1284.
- Ross, A., Leveritt, M., & Riek, S. (2001). Neural influences on sprint running: Training adaptations and acute responses. *Sports Medicine*, 31, 409-425.
- Rothstein, J. M., Miller, P. J., & Roettger, R. F. (1983). Goniometric reliability in a clinical setting: Elbow and knee measurements. *Physical Therapy*, 63, 1611-1615.
- Salamone, L. M., Fuerst, T., Visser, M., Kern, M., Lang, T., Dockrell, M., Cauley, J. A., Nevitt, M., Tylavsky, F., & Lohman, T. G. (2000). Measurement of fat mass using DEXA: A validation study in elderly adults. *Journal of Applied Physiology*, 89, 345-352.
- Salo, A., & Bezodis, I. (2004). Which starting style is faster in sprint running - standing or crouch start? *Sports Biomechanics*, 3, 43-53.
- Salo, A. I. T., Bezodis, I. N., Batterham, A. M., & Kerwin, D. G. (2011). Elite sprinting: Are athletes individually step-frequency or step-length reliant? *Medicine and Science in Sports and Exercise*, 43, 1055-1062.

- Salo, A. I. T., Keränen, T., & Viitasalo, J. T. (2005). Force production in the first four steps of sprint running. In Q. Wang (Ed.), *Proceedings of XXIII International Symposium on Biomechanics in Sport* (pp. 313-317). Beijing, China: The China Institute of Sport Science.
- Sands, W. A., McNeal, J. R., & Shultz, B. B. (1999). Kinetic and temporal patterns of three types of vertical jump among elite international divers. *Sports Medicine, Training and Rehabilitation*, 9, 107-127.
- Sands, W. A., Smith, L. S. L., Kivi, D. M. R., McNeal, J. R., Dorman, J. C., Stone, M. H., & Cormie, P. (2005). Anthropometric and physical abilities profiles: US National Skeleton Team. *Sports Biomechanics*, 4, 197-214.
- dos Santos, C. M., Ferreira, G., Malacco, P. L., Sabino, G. S., de Souza Moraes, G. F., & Felício, D. C. (2012). Intra and inter examiner reliability and measurement error of goniometer and digital inclinometer use. *Revista Brasileira de Medicina do Esporte*, 18, 38-41.
- Santos, D. A., Silva, A. M., Matias, C. N., Fields, D. A., Heymsfield, S. B., & Sardinha, L. B. (2010). Accuracy of DXA in estimating body composition changes in elite athletes using a four compartment model as the reference method. *Nutrition and Metabolism*, 7, 22.
- Sawade, C., Turnock, S., Forrester, A., & Toward, M. (2014). Assessment of an empirical bob-skeleton steering model. *Procedia Engineering*, 72, 447-452.
- Schot, P. K., & Knutzen, K. M. (1992). A biomechanical analysis of four sprint start positions. *Research Quarterly for Exercise and Sport*, 63, 137-147.
- Shellock, F. G., & Prentice, W. E. (1985). Warming-up and stretching for improved physical performance and prevention of sports-related injuries. *Sports Medicine*, 2, 267-278.
- Silva, A. M., Santos, D. A., Matias, C. N., Rocha, P. M., Petroski, E. L., Minderico, C. S., & Sardinha, L. B. (2012). Changes in regional body composition explain increases in energy expenditure in elite junior basketball players over the season. *European Journal of Applied Physiology*, 112, 2727-2737.

- Sjödén, B., & Jacobs, I. (1981). Onset of blood lactate accumulation and marathon running performance. *International Journal of Sports Medicine*, 2, 23-26.
- Slawinski, J., Bonnefoy, A., Levêque, J-M., Ontanon, G., Riquet, A., Dumas, R., & Chèze, L. (2010). Kinematic and kinetic comparisons of elite and well-trained sprinters during sprint start. *Journal of Strength and Conditioning Research*, 24, 896-905.
- Smilios, I., Pilianidis, T., Karamouzis, M., & Tokmakidis, S. P. (2003). Hormonal responses after various resistance exercise protocols. *Medicine and Science in Sports and Exercise*, 35, 644-654.
- Smilios, I., Tsoukos, P., Zafeiridis, A., Spassis, A., & Tokmakidis, S. P. (2014). Hormonal responses after resistance exercise performed with maximum and submaximum movement velocities. *Applied Physiology, Nutrition, and Metabolism*, 39, 351-357.
- Smith, A. A., Toone, R., Peacock, O., Drawer, S., Stokes, K. A., & Cook, C. J. (2013). Dihydrotestosterone is elevated following sprint exercise in healthy young men. *Journal of Applied Physiology*, 114, 1435-1440.
- Smith, C. A. (1994). The warm-up procedure: To stretch or not to stretch. A brief review. *Journal of Orthopaedic and Sports Physical Therapy*, 19, 12-17.
- Smith, D. J. (2003). A framework for understanding the training process leading to elite performance. *Sports Medicine*, 33, 1103-1126.
- Smith, G. (1989). Padding point extrapolation techniques for the Butterworth digital filter. *Journal of Biomechanics*, 22, 967-971.
- Smith, M. D., Jones, L. S., & Wilson, M. A. (2002). Sex differences in hippocampal slice excitability: Role of testosterone. *Neuroscience*, 109, 517-530.
- Smith, T. B., & Hopkins, W. G. (2011). Variability and predictability of finals times of elite rowers. *Medicine and Science in Sports and Exercise*, 43, 2155-2160.
- Snyder, E. M., Carr, R. D., Deacon, C. F., & Johnson, B. D. (2008). Overnight hypoxic exposure and glucagon-like peptide-1 and leptin levels in humans. *Applied Physiology Nutrition and Metabolism*, 33, 929-935.

- Staron, R. S., Malicky, E. S., Leonardi, M. J., Falkel, J. E., Hagerman, F. C., & Dudley, G. A. (1990). Muscle hypertrophy and fast fiber type conversions in heavy resistance-trained women. *European Journal of Applied Physiology and Occupational Physiology*, 60, 71-79.
- Staudenmayer, J., Zhu, W., & Catellier, D. J. (2012). Statistical considerations in the analysis of accelerometry-based activity monitor data. *Medicine and Science in Sports and Exercise*, 44, S61-S67.
- Stewart, A., & Ackland, T. (2011). Body composition: Laboratory and field methods of assessment. In M. Cardinale, R. Newton, & K. Nosaka (Eds.), *Strength and conditioning: Biological principles and practical applications* (pp. 318-333). Chichester, UK: John Wiley & Co.
- Stewart, A. D., & Hannan, J. (2000a). Sub-regional tissue morphometry in male athletes and controls using dual X-ray absorptiometry (DXA). *International Journal of Sport Nutrition and Exercise Metabolism*, 10, 157-169.
- Stewart, A. D., & Hannan, W. J. (2000b). Prediction of fat and fat-free mass in male athletes using dual X-ray absorptiometry as the reference method. *Journal of Sports Sciences*, 18, 263-274.
- Stokes, K. A. (2003). Growth hormone responses to sub-maximal and sprint exercise. *Growth Hormone and IGF Research*, 13, 225-238.
- Stokes, K. A., Gilbert, K. L., Hall, G. M., Andrews, R. C., & Thompson, D. (2013). Different responses of selected hormones to three types of exercise in young men. *European Journal of Applied Physiology*, 113, 775-783.
- Sutton, L., Scott, M., Wallace, J., & Reilly, T. (2009a). Body composition of English Premier League soccer players: Influence of playing position, international status, and ethnicity. *Journal of Sports Sciences*, 27, 1019-1026.
- Sutton, L., Wallace, J., Goosey-Tolfrey, V., Scott, M., & Reilly, T. (2009b). Body composition of female wheelchair athletes. *International Journal of Sports Medicine*, 30, 259-265.

- Tabachnik, B. G., & Fidell, L. S. (2007). *Using multivariate statistics*. (5th ed.). Boston, MA: Pearson.
- Tesch, P. (1988). Skeletal muscle adaptations consequent to long-term heavy resistance exercise. *Medicine and Science in Sports and Exercise*, 20, S132-S134.
- Thigpen, A. E., Silver, R. I., Guileyardo, J. M., Casey, M. L., McConnell, J. D., & Russell, D. W. (1993). Tissue distribution and ontogeny of steroid 5- α -reductase isozyme expression. *Journal of Clinical Investigation*, 92, 903-910.
- Thorstensson, A., Grimby, G., & Karlsson, J. (1976). Force-velocity relations and fiber composition in human knee extensor muscles. *Journal of Applied Physiology*, 40, 12-16.
- Tillin, N. A., Jimenez-Reyes, P., Pain, M. T. G., & Folland, J. P. (2010). Neuromuscular performance of explosive power athletes versus untrained individuals. *Medicine and Science in Sports and Exercise*, 42, 781-790.
- Toji, H., & Kaneko, M. (2004). Effect of multiple-load training on the force-velocity relationship. *Journal of Strength and Conditioning Research*, 18, 792-795.
- Toji, H., Suei, K., & Kaneko, M. (1997). Effects of combined training loads on relations among force, velocity, and power development. *Canadian Journal of Applied Physiology*, 22, 328-336.
- Toone, R. J., Peacock, O. J., Smith, A. A., Thompson, D., Drawer, S., Cook, C., & Stokes, K. A. (2013). Measurement of steroid hormones in saliva: Effects of sample storage condition. *Scandinavian Journal of Clinical and Laboratory Investigation*, 73, 615-621.
- Trewin, C. B., Hopkins, W. G., & Pyne, D. B. (2004). Relationship between world-ranking and Olympic performance of swimmers. *Journal of Sports Sciences*, 22, 339-345.
- Twist, C., & Eston, R. (2005). The effects of exercise-induced muscle damage on maximal intensity intermittent exercise performance. *European Journal of Applied Physiology*, 94, 652-658.

- UK Sport (2015). Historical funding figures. Available from <http://www.uksport.gov.uk/our-work/investing-in-sport/historical-funding-figures>. [Accessed 18 March 2015].
- Urhausen, A., Gabriel, H., & Kindermann, W. (1995). Blood hormones as markers of training stress and overtraining. *Sports Medicine*, 20, 251-276.
- Vagenas, G., & Hoshizaki, T. B. (1986). Optimization of an asymmetrical motor skill: Sprint start. *International Journal of Sport Biomechanics*, 2, 29-40.
- Vantorre, J., Seifert, L., Fernandes, R. J., Boas, J. P. V., & Chollet, D. (2010). Comparison of grab start between elite and trained swimmers. *International Journal of Sports Medicine*, 31, 887-893.
- Viganò, A., Ripamonti, M., De Palma, S., Capitanio, D., Vasso, M., Wait, R., Lundby, C., Cerretelli, P., & Gelfi, C. (2008). Proteins modulation in human skeletal muscle in the early phase of adaptation to hypobaric hypoxia. *Proteomics*, 8, 4668-4679.
- Viitasalo, J. T., & Bosco, C. (1982). Electromechanical behaviour of human muscles in vertical jumps. *European Journal of Applied Physiology*, 48, 253-261.
- Viru, A., & Viru, M. (2001). *Biochemical monitoring of sport training*. Champaign, IL: Human Kinetics.
- Viru, A., & Viru, M. (2004). Cortisol - essential adaptation hormone in exercise. *International Journal of Sports Medicine*, 25, 461-464.
- Volkov, N. I., & Lapin, V. I. (1979). Analysis of the velocity curve in sprint running. *Medicine and Science in Sports and Exercise*, 11, 332-337.
- Wang, C., Plymate, S., Nieschlag, E., & Paulsen, C. A. (1981). Salivary testosterone in men: Further evidence of a direct correlation with free serum testosterone. *Journal of Clinical Endocrinology and Metabolism*, 53, 1021-1024.
- Weir, J. P. (2005). Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. *Journal of Strength and Conditioning Research*, 19, 231-240.

West, D. W. D., Burd, N. A., Tang, J. E., Moore, D. R., Staples, A. W., Holwerda, A. M., Baker, S. K., & Phillips, S. M. (2010). Elevations in ostensibly anabolic hormones with resistance exercise enhance neither training-induced muscle hypertrophy nor strength of the elbow flexors. *Journal of Applied Physiology*, 108, 60-67.

West, D. W. D., Kujbida, G. W., Moore, D. R., Atherton, P., Burd, N. A., Padzik, J. P., De Lisio, M., Tang, J. E., Parise, G., Rennie, M. J., Baker, S. K., & Phillips, S. M. (2009). Resistance exercise-induced increases in putative anabolic hormones do not enhance muscle protein synthesis or intracellular signalling in young men. *Journal of Physiology*, 587, 5239-5247.

West, D. W. D., & Phillips, S. M. (2012). Associations of exercise-induced hormone profiles and gains in strength and hypertrophy in a large cohort after weight training. *European Journal of Applied Physiology*, 112, 2693-2702.

Weyand, P. G., Sternlight, D. B., Bellizzi, M. J., & Wright, S. (2000). Faster top running speeds are achieved with greater ground forces not more rapid leg movements. *Journal of Applied Physiology*, 89, 1991-1999.

Wilson, G. J., Murphy, A. J., & Walshe, A. (1996). The specificity of strength training: The effect of posture. *European Journal of Applied Physiology and Occupational Physiology*, 73, 346-352.

Wilson, G. J., Newton, R. U., Murphy, A. J., & Humphries, B. J. (1993). The optimal training load for the development of dynamic athletics performance. *Medicine and Science in Sports and Exercise*, 25, 1279-1286.

Winchester, J. B., Nelson, A. G., Landin, D., Young, M. A., & Schexnayder, I. C. (2008). Static stretching impairs sprint performance in collegiate track and field athletes. *Journal of Strength and Conditioning Research*, 22, 13-19.

Wing-Gaia, S. L. (2014). Nutritional strategies for the preservation of fat free mass at high altitude. *Nutrients*, 6, 665-681.

Winter, D. A., Sidwall, H. G., & Hobson, D. A. (1974). Measurement and reduction of noise in kinematics of locomotion. *Journal of Biomechanics*, 7, 157-159.

- Winter, E. (2008). Use and misuse of the term "significant". *Journal of Sports Sciences*, 26, 429-430.
- Winter, E. M., Abt, G. A., & Nevill, A. M. (2014). Metrics of meaningfulness as opposed to sleights of significance. *Journal of Sports Sciences*, 32, 901-902.
- Wisløff, U., Castagna, C., Helgerud, J., Jones, R., & Hoff, J. (2004). Strong correlation of maximal squat strength with sprint performance and vertical jump height in elite soccer players. *British Journal of Sports Medicine*, 38, 285-288.
- Wolf, P. L., Lott, J. A., Nitti, G. J., & Bookstein, R. (1987). Change in serum enzymes, lactate and haptoglobin following acute physical stress in international-class athletes. *Clinical Biochemistry*, 20, 73-77.
- Yarrow, J. F., McCoy, S. C., & Borst, S. E. (2012). Intracrine and myotrophic roles of 5 α -reductase and androgens: A review. *Medicine and Science in Sports and Exercise*, 44, 818-826.
- Yeadon, M. R., & Challis, J. H. (1994). The future of performance-related sports biomechanics research. *Journal of Sports Sciences*, 12, 3-32.
- Yeadon, M. R., Kato, T., & Kerwin, D. G. (1999). Measuring running speed using photocells. *Journal of Sports Sciences*, 17, 249-257.
- Young, W. (1995). Laboratory strength assessment of athletes. *New Studies in Athletics*, 10(1), 89-96.
- Young, W., McLean, B., & Ardagna, J. (1995). Relationship between strength qualities and sprinting performance. *Journal of Sports Medicine and Physical Fitness*, 35, 13-19.
- Young, W. B. (2006). Transfer of strength and power training to sports performance. *International Journal of Sports Physiology and Performance*, 1, 74-83.
- Zanoletti, C., La Torre, A., Merati, G., Rampinini, E., & Impellizzeri, F. M. (2006). Relationship between push phase and final race time in skeleton performance. *Journal of Strength and Conditioning Research*, 20, 579-583.

APPENDIX: METHODS TO EVALUATE SKELETON START PERFORMANCE PROGRESSION ACROSS ICE-TRACK COMPETITIONS

A.1. Start performance data

The longitudinal changes in start performance (across three seasons from 2011/12 to 2013/2014) for the seven (four female, three male) elite squad British skeleton athletes involved in all studies presented in this thesis were the focus of this analysis. Thus, official start time data from every international race across this period (in which any of the seven athletes competed in) were obtained from the publicly available International Bobsleigh and Skeleton Federation website (FIBT, 2015a). Data from all levels of competition were included in the analysis: Winter Olympic Games, World Championships, World Cup, Intercontinental Cup and Europa Cup races.

A.2. Matching procedure

To account for inter-competition variation in start times, data from the British skeleton athletes could only be compared with fellow competitors, who competed in exactly the same event (same track on the same day). Thus, a ‘matching’ procedure was adopted to identify athletes from other nations who competed in multiple races against one of the British athletes, in all three seasons. Frequent alterations to squad selections during competition seasons are common in skeleton, and thus, the circuit on which athletes compete will often change between, and sometimes within, seasons. This can somewhat restrict the number of possible matches which can be made across races and seasons. Table A.1 summarises the data included in the analysis.

A.3. Statistical analysis

For each run included in the analysis, average start velocity was calculated by dividing the start phase length (50 m) by the start (15-65 m) time. When races consisted of multiple heats (runs), a mean start velocity was calculated for each athlete. Percentage differences for the start velocities achieved by British athletes compared with fellow competitors (‘start velocity difference’) were then computed for each race (with positive values indicating that the British athlete performed a faster start than their competitors). For each fellow competitor, an average start velocity difference was computed for all matched races across each separate season. These averages were then used to calculate a mean and standard deviation start velocity difference for each British athlete.

Additionally, group means and standard deviations were calculated to reflect the overall start velocity difference for all seven British athletes. Longitudinal changes in the group mean start velocity differences were assessed using standardised differences (effect sizes; Cohen, 1988). Confidence intervals (90% CI) were calculated and magnitude-based inferences derived as previously suggested (Batterham and Hopkins, 2006), using a published spreadsheet (Hopkins, 2006d). Effect sizes were interpreted in exactly the same way as in a previous chapter (Chapter 3, section 3.2.4).

Table A.1. Average number of matched competitors, tracks per season, and races and runs per fellow competitor included in the comparative analysis for each of the seven British athletes.

Athlete	Matched athletes	Different tracks per season	Races per season for each matched competitor	Runs per season for each matched competitor
A1	2	6	6	13
A2	4	8	7	14
A3	3	3	4	9
A4	4	6	4	8
A5	2	6	5	9
A6	3	5	4	8
A7	4	4	6	11
Mean \pm SD	3 \pm 1	6 \pm 2	5 \pm 1	10 \pm 2